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VIVIENDA LOS MAÑÍOS

Inmersa en los bosques de la Décima Región de Chile, sector de Chamiza, perteneciente a la Comuna de Puerto Montt. Su sistema constructivo es realizado con fardos de paja de trigo, combinado con estructura de madera como soporte. El *diseño pasivo* de esta vivienda considera una eficiente envolvente térmica utilizando al fardo de paja de trigo en sus muros exteriores, y orientando la mayor superficie de vanos hacia el norte maximizando las ganancias solares e iluminación natural. Además este proyecto incorpora recintos propios del habitar de la zona sur de Chile, como ser el espacio de chiflonera y el flojero; asiento en torno a la cocina a leña. La vivienda resalta las materialidades y técnicas constructivas en madera propias de la zona sur de Chile.

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EDITORIAL

ARQUITECTURA MÁS ALLÁ DE LA SUSTENTABILIDAD

Es un hecho que la pandemia Covid 19 ha impactado no solo nuestras vidas, sino también la disciplina de la arquitectura, que ha alzado la mirada hacia la salud y bienestar de las personas que habitan espacios arquitectónicos. La verdad es que el bienestar de los ocupantes ha sido materia de interés disciplinar desde ya hace varios años, pero se ha visto enfatizado aún más con los requerimientos de higienización y calidad ambiental de los espacios, derivados de la pandemia. Hoy, esperamos que la arquitectura sustentable no solo apunte a mitigar los impactos negativos que las edificaciones generan sobre el medio ambiente sino también entregue espacios saludables, confortables, centrados en los habitantes. De esta manera, la agenda de sustentabilidad en la arquitectura, usualmente orientada hacia aspectos ambientales como energía cero, eficiencia hídrica o economía circular, comienza a abarcar la dimensión social con mucha más fuerza. Quizás esta tendencia surge en parte como reacción a los edificios de alto desempeño que mantienen la lógica de la arquitectura internacional del siglo XX –un estilo arquitectónico para todos los climas– donde una envolvente con materiales altamente tecnologizados, sistemas de climatización e iluminación sofisticados y eficientes permiten eficientes desempeños ambientales en distintos contextos. Actualmente, en distintas partes del mundo, se aboga por una arquitectura más "humanizada".

El bienestar en espacios arquitectónicos es un tema que ha sido investigado, publicado, y que forma parte de estándares y de sistemas de certificación de edificios, tales como WELL y Fitwell. Sin embargo, se trata de un constructo que aún no ha sido adecuadamente definido y, por lo tanto, resulta difícil determinar cómo diseñar, medir y proveer de bienestar a través de la arquitectura. Tradicionalmente, el foco ha estado puesto en aspectos físicos de la calidad del ambiente interior, es decir, temperatura, iluminación, ruidos y calidad del aire, que se traducen en indicadores y estándares medibles y verificables. Estas dimensiones del ambiente interior influyen en la percepción de los ocupantes y en su confort para desempeñar las tareas cotidianas. No obstante, el bienestar y la salud exigen una mirada holística que responde a aspectos físicos, psicológicos y fisiológicos.

Más allá de la percepción momentánea de comodidad, el bienestar se relaciona con los efectos que el espacio arquitectónico genera sobre los seres humanos en el mediano y largo plazo. Un ejemplo de ello son justamente las secuelas de las cuarentenas, que han obligado a las personas a permanecer por tiempos prolongados en espacios interiores, a partir de lo cual ha aumentado la deficiencia de vitamina D y calcio, por falta de sol, entre otras patologías. El ciclo solar se conecta a través de la visión con el ciclo circadiano del cuerpo para coordinar los ritmos diarios y estacionales de casi todos los procesos de nuestros cuerpos. Los patrones de iluminación, con días luminosos y noches oscuras, además de las variaciones en el color de la luz entre el amanecer y el atardecer, se alinean con las hormonas para proveer de escenarios saludables. Pero el bienestar no solo implica la ausencia de enfermedad, sino que las maneras en que los espacios arquitectónicos agregan valor a la vida de las personas. Espacios conectados con la naturaleza capaces de nutrir la experiencia arquitectónica y generar impactos positivos sobre el medio ambiente, de bioremediación.

Es claro que el futuro de la disciplina nos plantea nuevos desafíos, tanto para la investigación como para la innovación y el diseño arquitectónico. La revista Hábitat Sustentable surge, en este escenario, como una instancia de reflexión y debate sobre estos temas, donde la perspectiva latinoamericana tiene ciertamente mucho que aportar, ya sea por una tradición de arquitectura con sentido de lugaridad, como por los desafíos derivados de las desigualdades sociales.

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GLAZED CURTAIN WALLS: THERMAL TRANSMITANCE CALCULATION

FACHADAS VIDRIADAS: CÁLCULO DE TRANSMITANCIA TÉRMICA

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RESUMEN

La piel de vidrio es uno de los elementos dominantes de la arquitectura moderna y contemporánea. Este diseño de envolvente puede influir significativamente en la demanda de energía operativa de los edificios. En este trabajo, se analizan los sistemas de fachada de piel de vidrio disponibles en Argentina, con el objetivo de determinar los rangos de transmitancia térmica asociados, en función del diseño de perfiles, del tipo de vidriado y de las dimensiones de los paños vidriados. Inicialmente, se estudia mediante cálculo numérico bidimensional el impacto de varios parámetros de diseño de los perfiles sobre la transmitancia térmica, destacando la relevancia del modo de fijación del vidriado, para luego calcular la transmitancia térmica de las fachadas completas. Los resultados indican que el valor de transmitancia térmica de las fachadas de piel de vidrio depende principalmente de la transmitancia del vidriado empleado, y supera la misma en un 24%, en promedio.

Palabras clave
fachadas, piel de vidrio, índices, sistemas constructivos.

ABSTRACT

Glazing is one of the dominant features of modern and contemporary architecture. This envelope design may have a great impact on operational energy demand of buildings. In this work, glazed façade systems available in Argentina are analyzed, with the purpose of determining the associated thermal transmittance ranges, in terms of the profiles' design, the type of glazing and the size of glass panes. First, by using bidimensional numerical calculation, the impact of several profile design parameters on thermal transmittance is studied, highlighting the relevance of glazing fixing methods, to then calculate the thermal transmittance of the entire facade. The results indicate that the thermal transmittance value of glazed facades, mainly depends on the transmittance of the glass used, and exceeds this by 24% on average.

Keywords
façades, glazing, indices, construction systems

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INTRODUCTION

The way our habitat is built, cannot just be focused on seeking architectural functionality and aesthetics. It must also consider the sustainability of the built space, looking to reduce global final energy consumption and greenhouse gas emissions. The environmental impact of the building sector has been rising in recent decades (Cao, Dai & Liu, 2016), and reversing this trend is a great challenge which numerous countries have already embarked upon. The road to reach this goal, can be classified in three categories: the passive design and energy conservation strategies, the energy efficiency technologies for building operation; and energy production using renewable energies (D'Amanzo, Mercado & Karlen, 2020). Within the first category, one can find the design of the building envelope, which has an impact on the operational energy demand.

One of the envelope characteristics that most affects the heating and cooling energy consumption of buildings is the window-to-wall ratio (WWR) (Lam, Ge & Fazio, 2016; de Gastines & Pattini, 2020). In this sense, Aste, Buzzetti, Del Pero and Leonforte (2018) analyzed heating, cooling and lighting consumption in offices located in cities with different climates (Athens, Stockholm and Milan), and saw that, in the absence of shading elements, the WWR has a noticeable impact on energy demands (up to 60% difference between cases with WWR of 20% and 80%). Hence, fully glazed building envelopes with integrated facades represent a challenge for designers, who have to try to control thermal energy flows through these envelopes. For this, knowledge of the energy indicators of integrated façade systems is essential. Despite the great role of glazing, whose thermal properties are well documented, in these envelopes, the latticework support of the integrated façade can significantly affect the thermal transmittance value (U) of the façade (De Gastines & Pattini, 2019a). This is due to the high conductivity of the aluminum used to manufacture profiles, and the low compactness that they tend to have (De Gastines & Pattini, 2019b), which leads to a higher exposure to the interior and/or exterior film coefficients (convection and radiation). In addition, despite being hidden behind the glazing, the projected surface of the latticework can be important and significantly affect the thermal transmittance of the façade system (Bae, Oh & Kim, 2015).

At an international level, it has been sought to improve the energy performance of integrated façade systems using insulating materials, including the thermal bridge breaker, triple hermetically sealed glazing, thermochromic glazing (Arnesano *et al.*, 2021), polyester reinforced with fiber glass (Cordero, 2015), or through the use of a double envelope, where the glazed façade conceals another low thermal transmittance skin (Bronwyn, 2018), or allows building a ventilated chamber (Saroglou, Meir & Theodosiou, 2020). The main innovation in integrated façade systems is the integration of semi-transparent photovoltaic nodules on parts of the façade that receive more solar radiation (Mocerino, 2020; Wu & Flemmer, 2020). However, these strategies are associated to a high initial cost, that limits their general use in developing countries.

The energy indices of integrated façade systems used in Argentina, have not yet been characterized in detail. The data that is available is limited to the properties of the glazing (IRAM 11601, 2002) and the traditional window systems (de Gastines & Pattini, 2019b), along with the study of a glazing skin façade design (de Gastines & Pattini, 2019b). However, it is possible that the thermal transmittance values of integrated façade systems vary considerably considering the design variants there are.

The glazed skin is an integrated façade system that consists in a latticework comprised by vertical load bearing profiles and horizontal aluminum crossbeams, which once assembled on site, allow inserting aluminum and glass sheets. This is one of the dominant elements of modern contemporary architecture (Viteri, 2020), generally used to achieve a completely glazed outside face, where the metal structure is hidden behind tonal glass, and fixed with glue or through small glazing moldings. It is often used in commercial and medium to large scale office buildings, and to a lesser extent, in the residential sector. This construction system has numerous advantages for buildings with several floors, including its easy assembly, the light weight (especially relevant for seismic areas), the watertightness, as well as a luminous and comfortable indoor environment (Hamida & Alshibani, 2020; Yalaz, Tavil & Celik, 2018; Huang, Chen, Lu & Mosalam, 2017), as long as the control of undesired solar radiation is guaranteed.

The purpose of this work is based on analyzing the glazed skin façade systems available in Argentina, and to determine the associated thermal transmittance value ranges, considering the profile design used, the type of glazing, and the sizes of the glazed panels.

METHODOLOGY

ANALYSIS OF PROFILE DESIGN VARIANTS

A revision of the product catalogs offered by six Argentinean companies for integrated façade profile extruders allowed defining a representative range of glass skin façade construction systems.

There are different parameters to consider to choose the glazed skin system. First, the profiles must adapt

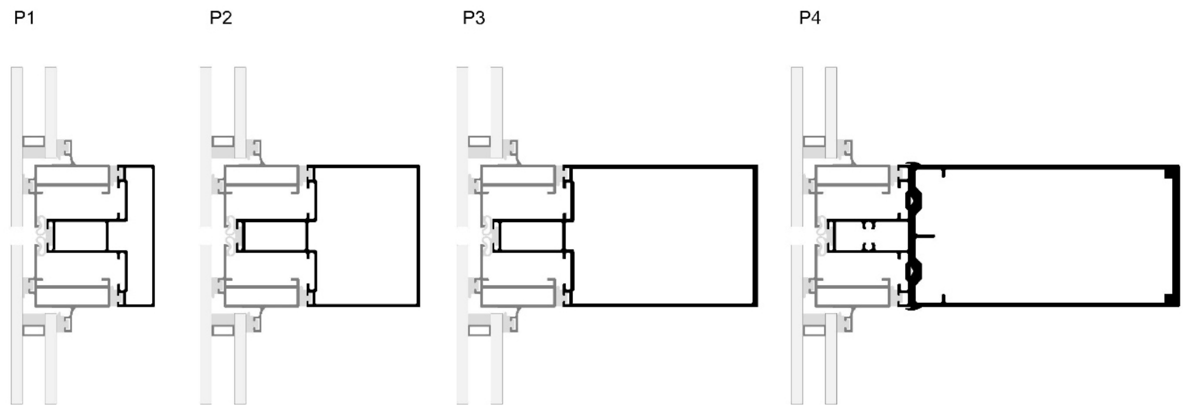

Figure 1. Variation of the column length (from left to right: 57 mm, 97 mm, 140 mm, 186 mm). Source: Preparation by the Authors.

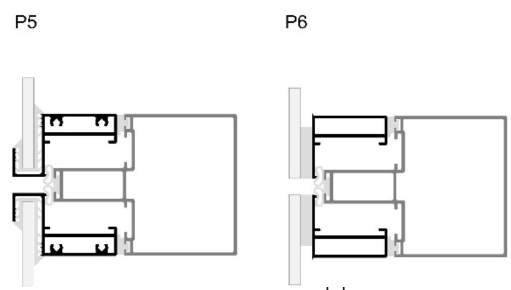

Figure 2. Comparison between the glazing fixtures: contained (section P5) and glued (section P6) Source: Preparation by the Authors.

to the chosen glazing width, which varies greatly depending on whether this is simple glazing (SG), or hermetically sealed double glazing (HDG). These also fit the panel opening (fixed panel (FP) or mobile panel (MP)). Finally, the profiles differ depending on whether the glazing is contained (whether capsulated, or fixed using glazing moldings) or glued (using structural silicon or VHB tape). There is also a sheet variant for the offset HDG. This variant allows installing HDG and SG together in certain parts of the façade (for example, in front of slabs of multi-floor buildings), keeping the same external edges on the entire façade.

Given the great variety of profile options, parameters were highlighted that could significantly affect the thermal transmittance values of the profiles, studying the relevance of each one separately, to select a smaller sample of profiles for the later analysis of the entire façade system. The parameters revealed are detailed below.

Wall supports (horizontal shear)

Parameter 1: Column length. The column profile bears the load of the façade, which is why it must be chosen considering the dimensions of the glazed panels and the weight of the glazing, to achieve the necessary mechanical resistance. The surveying made, allowed highlighting that the column lengths common to most of the manufacturers are 57 mm, 97 mm and 140 mm. There are longer profiles, whose dimensions differ depending on the manufacturer, with the longest being 186 mm (dividing column and supplementary column assembly). It is considered that the column length may be a factor that significantly impacts the thermal transmittance value of the latticework, as it generates different degrees of interior compactness of its vertical sections.

Figure 1 graphically shows the four sections analyzed, where the column profile's length varies depending on the aforementioned measurements.

Parameter 2: Contained or glued glass. Although there are several ways to attach the glazing, from a thermal point of view, two types of sections are distinguished. The first, with contained glass (i.e. encapsulated or fixed using glazing moldings), where a thermal bridge is generated between the inside and outside by the sheet profile; and the second, with glued glass, where the metal profiles are insulated from the outside through the glazing, silicon, and a partly ventilated cavity in the joint between glazed panels.

Figure 2 shows the two sections chosen to compare the impact of the type of glazing fixture on the thermal transmittance value.

Parameter 3: Offset HDG. The offset HDG setup increases the projected width of the wall support,

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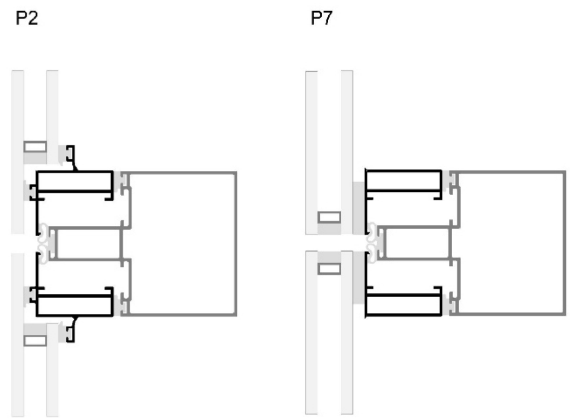

Figure 3. Comparison between wall support with offset (section P2) and glued (section P7) HDG setup. Source: Preparation by the Authors.

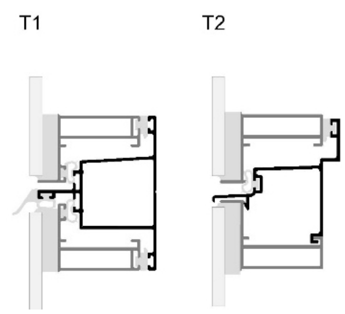

Figure 4. Crossbeam profile design variants: with cavity (left) and with water draining (right). Source: Preparation by the authors.

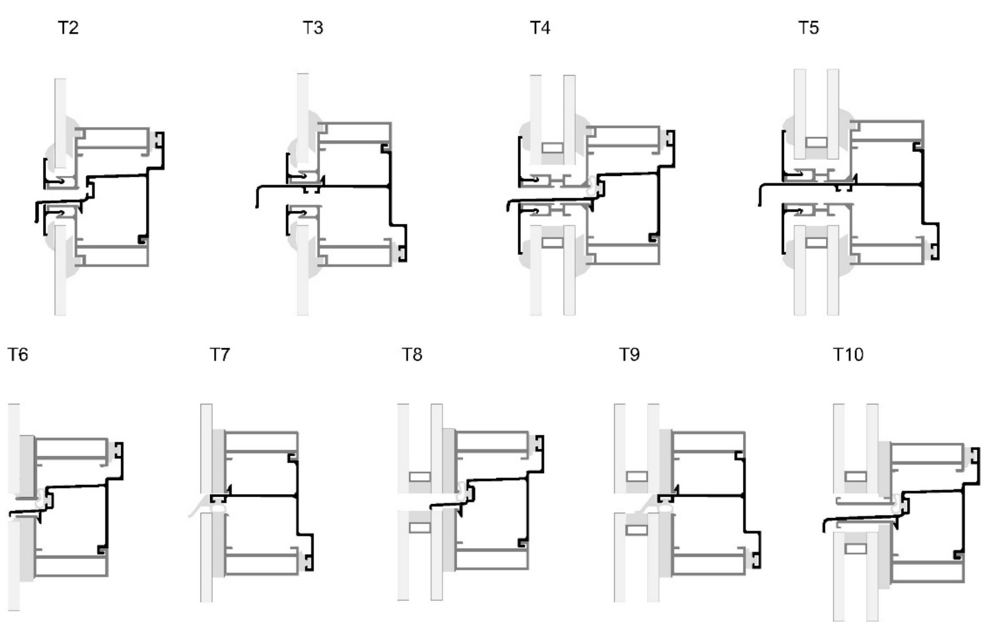

Figure 5. Horizontal interstitial space design variants: setups with contained glazing (above) and glued glazing (below). Options with SG or HDG, and fixed panel (even numbers) or mobile panel (odd numbers) header. T10 is a variant of section T8 with water drains jutting out. Source: Preparation by the authors.

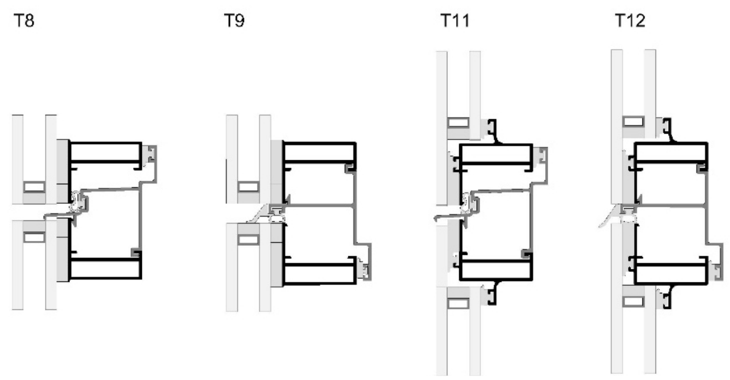

Figure 6. Comparison of the glued (T8: FP variant and T9: MP variant) and offset (T11: FP variant and T12: MP variant) HDG setups. Source: Preparation by the Authors.

as well as slightly reducing the surface of profiles exposed to the interior border conditions. To know the impact of this parameter, section P2 (with median column and offset HDG) is compared with a similar variant, but with glued HDG (P7) (Figure 3)

Crossbeams (vertical sections)
Parameter 4. Crossbeam design. 2 types of crossbeam profiles are seen, one common to two of the catalogs analyzed, with a cavity, and another common to the other four catalogs, called "water draining" (Figure 4). On having different morphologies, in particular different amounts and dimensions of internal cavities, they could also have different thermal transmittance values.

Parameter 5: Horizontal interstitial space. Among the crossbeam profile variants with water draining, 9 similar design options were highlighted regarding their interior profile (same projected width and compactness coefficient), which are different from one another, essentially because of the length of the water drain at the level of the interstitial space between glazed panels, and due to the presence or absence of glazing moldings. Depending on the type of glazing (SG / HDG), the type of opening (FP/ MP), and the means of fixing the glazing (contained/ glued), the water drain may or may not jut outside the façade, generating or not generating a thermal bridge. Likewise, the variation in length modifies the external compactness coefficient of the profile, thus being able to affect its thermal transmittance value.

Parameter 6. Offset HDG. The offset HDG setup increases the projected width of the crossbeam, as well as slightly reducing the surface of profiles exposed to internal border conditions. Here the crossbeam sections (FP and MP variants) were compared with glued HDG and offset HDG, as can be seen in Figure 6.

Projected section width
Finally, the projected width of the different profiles is compared, which will determine the final thermal transmittance value of the façade system (as this depends on the percentage of the façade surface occupied by the metal latticework).

CASE STUDY SELECTION

Metal profiles
After having isolated the parameters chosen to analyze the impact of each one on the thermal transmittance values, and to identify the most relevant parameters, the study concentrated on the latter.

It is worth clarifying that this work does not consider the analysis of the lower, upper or lateral finishings, nor the corners and swivel joints, as it is assumed that said profiles occupy a small percentage of the façade surface.

Glazing
The glazing generally used on glass skin facades is solar control HDG glued with structural silicon, that allows limiting solar gains, avoiding the overheating of the building and, at the same time, hides the metal latticework, achieving a completely glazed view.

It is proposed to study the following glazing options, that address a broad range of thermal transmittance values:

- G1: Reflective solar control and low emissivity HDG (Eclipse Advantage Evergreen 6 mm / 12 mm air chamber / 6 mm colorless float).
- G2: High reflectance and solar control HDG (Cool Lite STB 120 6 mm / 12 mm air chamber / 6 mm colorless float).
- G3: solar control pyrolytic reflective SV and low emissivity (Eclipse Advantage Evergreen 6 mm).
- G4: Solar control and high reflectance SV (Cool Lite ST136 6 mm).

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Panel sizes

The construction system under analysis allows a certain degree of freedom in the sizing of glazed panels, as long as the static use limits are respected, which are related to the distance between columns (panel width), and the distance (height) between the supporting or anchoring points to the building's structure, calculated considering the wind pressure and column profile used. It is also recommended, that panel sizes do not exceed 1.25 m x 1.50 m (width by height).

In practice, and in general, one seeks to optimize glass use, which come in 2.40 m x 3.60 m sheets. Also the incorporation of mobile panels implies horizontal divisions that tend to be a fixed sill panel, an intermediate mobile panel and a fixed lintel panel.

Three glazed panel sizes are compared in this study. The largest comprising panels that are 1.20 wide by 1.50 m high; the intermediate of 1.20 m by 1.00 m; and the smallest, of 0.80m by 1.00 m.

CALCULATION PROCEDURE

In the following stage, the sections chosen were simulated using the WINDOW 7.7 and THERM7.7 programs, developed by LBNL (Lawrence Berkeley National Laboratory). WINDOW allows calculating the thermal transmittance of the glazing (U_g), while the woodwork profile sections are simulated in THERM. This program uses the finite elements method to calculate heat flows in the studied component, considering the indicated environmental conditions. In this way, it produces the transmittance value of the frame (U_f) and of the glazed edge (U_e), which corresponds to a perimetral strip of 63.5 mm, where the border effects between the frame and the glazing appear. Figure 7 indicates the different parts of the integrated façade system (center of the glazing, border, frame/wall support or crossbeam sheet profile).

Representative environmental conditions of a winter day in Buenos Aires (de Gastines & Pattini, 2019b) were considered, as outlined in Table 1. The conductivity values considered for the different materials that the façade system comprises, are shown in Table 2.

The U_g values of the glazing were calculated using WINDOW. Then, the wall support and crossbeam sections were simulated in THERM twice, successively inserting glazing G3 and G4 (sections with SG) or G1 or G2 (sections with HDG), to obtain the corresponding U_f and U_e values. Once the thermal indices of the different parts of the integrated façade system were obtained, the weighted average by their area (U) was calculated, for the different proposed glazing panels sizes.

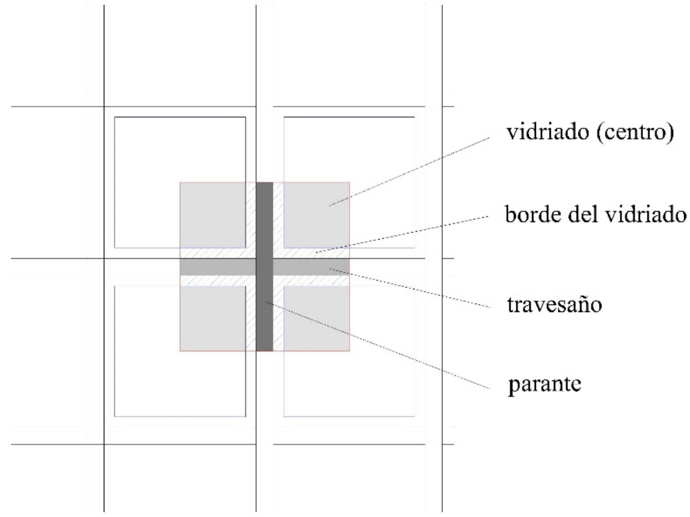


Figure 7. Base module of the integrated façade system, identifying its different parts. Source: Preparation by the Authors.

To	Tro	hco	Ti	Tri	hci
12.9°C	12.9°C	9.33 W/ m2K	21°C	21°C	3.29 W/ m2K

Table 1. Environmental conditions used to calculate thermal transmittance, where Ti and To are the indoor and outdoor air temperatures, respectively; Tri and Tro are respectively, the indoor and outdoor mean radiant temperatures; and hci and hco are the convective indoor and outdoor coefficients, respectively, Source: Preparation by the Authors, 2019b

Material	Conductivity (W(mK)
Aluminum	199
EPDM weather strip	0,25
Silicon	0,35 (Carbary y Kimberlain, 2020)

Table 2. Conductivity values considered in this research. Source: Preparation by the Authors.

RESULTS AND DISCUSSION

PROFILE THERMAL TRANSMITTANCE

The thermal transmittance values, U_f, of the simulated sections are presented in Figure 8. Below, the relevance of the different wall supports, highlighted above, are analyzed.

Parameter 1: Column length. The variation of thermal transmittance values considering the column length is seen in Figure 9, comparing the Uf values of sections P1, P2, P3 and P4. A significant difference is seen between the

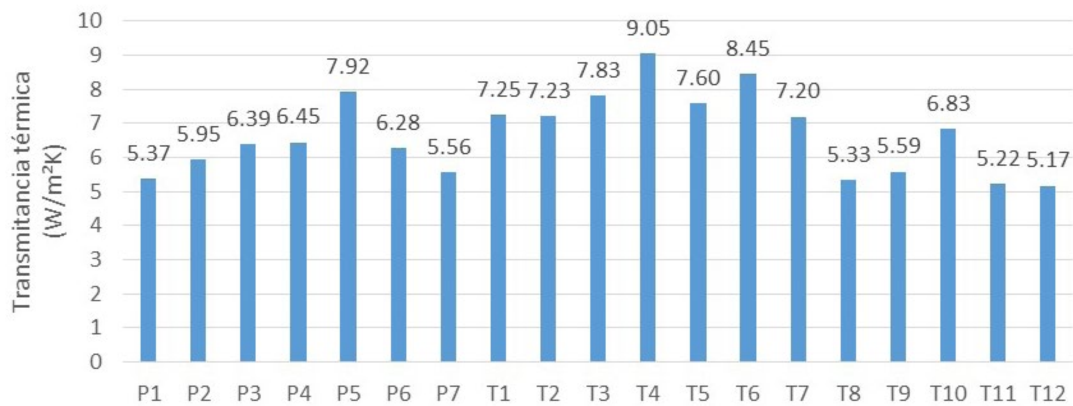
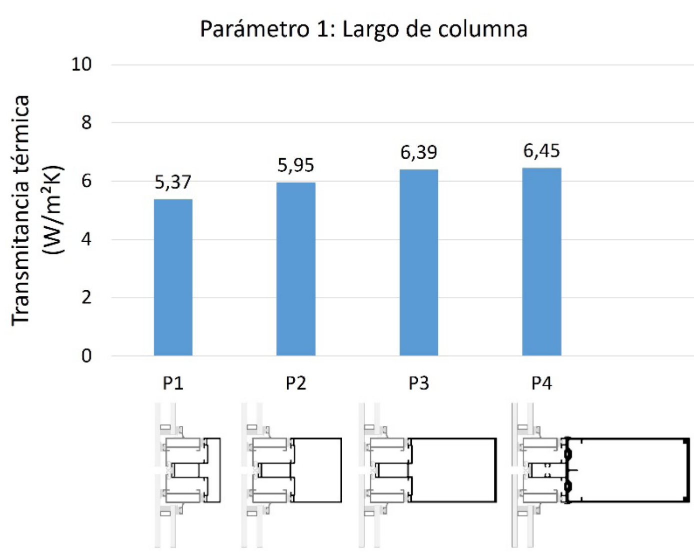


Figure 8. Thermal transmittance values (in W/m2K) of the sections analyzed. Source: Preparation by the Authors.



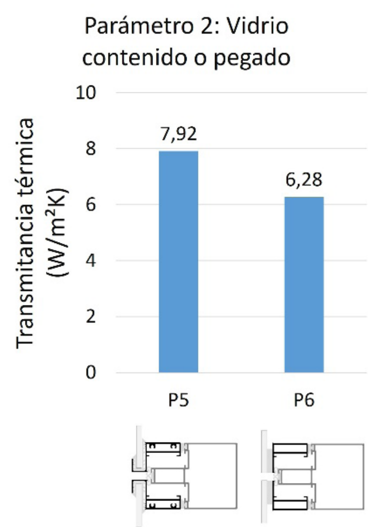
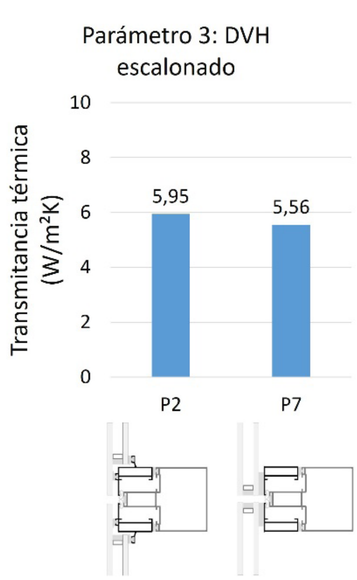


Figure 9. Effect of the column length on the thermal transmittance value.Source: Preparation by the Authors.
Figure 10. Effect of glazing fixture method on the thermal transmittance value. Source: Preparation by the Authors.



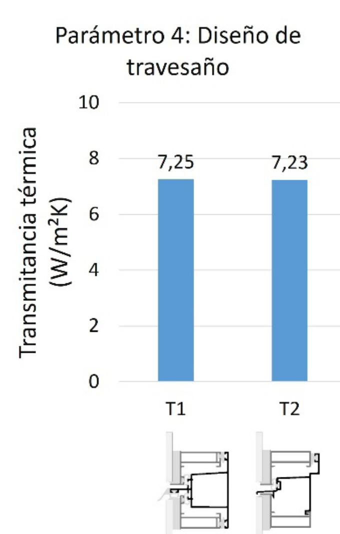


Figure 11. Effect of the offset HDG on the thermal transmittance value of the supporting wall. Source: Preparation by the Authors
Figure 12. Effect of the crossbeam design on the thermal transmittance value. Source: Preparation by the Authors.

thermal transmittance of the first three sections (absolute difference of 1.02 W/m2K between P1 and P3), while the fourth (with reinforced columns) has a Uf value similar to that of section P3.

Parameter 2: Contained or glued glass. Comparing the U_f values obtained through the simulation of sections P5 and P6 (Figure 6), an important difference is seen (1.64 W/m²K) between the thermal transmittance of the supporting wall with contained (section P5) and glued (section P6) setups. The variant with glued glass has a better thermal performance, given that it avoids the thermal bridge associated to glazing moldings or to the sheet profile for encapsulated glass.

Parameter 3: offset HDG. The comparison between the U_f values of sections P2 and P7 (Figure 11), allows analyzing the difference regarding the thermal flow between the offset HDG (P2) and glued HDG (P7) setups on supporting walls. The offset HDG produces a slight increase of the heat transfers (0.39 W/m²K).

Parameter 4: Crossbeam design. As can be seen in Figure 12, the two crossbeam variables, T1 and T2 (with cavity and water drains, respectively), have the same thermal transmittance value (insignificant difference of 0.02 W/m²K). Therefore, this parameter is not relevant

Parameter 5: Horizontal interstitial space. The comparison of the U_f values of sections T2 to T10 (Figure 13) reveal that the design of the horizontal interstitial space between panels has a great impact on the thermal transmittance of the crossbeam (maximum difference of 3.72 W/m²K).

The minimum values are obtained in the setups with glued HDG, T8 and T9 (5.33 and 5.59 W/m²K, respectively), where the HDG and the interstitial cavity act as a thermal bridge breaker between the metal profile and the outside of the façade. The variant, T10 with glued HDG, but with water drain jutting out, obtains a higher U_f value (6.83 W/m²K), due to the thermal bridge that this generates.

Then, in sections T6 and T7 (7.23 and 7.20 W/m²K, respectively), it is seen that these are identical to sections T8 and T9, but with glued single glazing (fixed and mobile). On the glazing being narrower, the water draining profiles jut outside the façade and generate a thermal bridge, as such the thermal transmittance values significantly rise in comparison to sections T8 and T9.

The crossbeam sections with contained glazing (T2 to T5) obtain higher thermal transmittance values than sections with glued glass, as also happens in the wall supports. Comparing the sections with fixed panel, T2 and T4 (7.83 and 7.60 W/m²K, respectively), and the mobile panel sections, T3 and T5 (9.05 and 8.45 W/m²K, respectively), the latter have the highest thermal transmittance values. In a façade setup with fixed sill and lintel and intermediate mobile panel, the two crossbeam variants are used simultaneously, therefore, the U_f values obtained can be averaged, leaving a value of 8.03 W/m²K for the crossbeam with contained HDG, and 8.44 W/m²K for the crossbeam with contained single glazing.

Parameter 6: Offset HDG. In Figure 14, sections T11 and T12 (crossbeams with offset HDG, fixed panel and mobile panel head, respectively), with sections T8 and T9 (identical, but with glued HDG). Their thermal transmittance values differ in 0.11 W/m²K (T8 – T11) and 0.42 W/m²K (T9 – T12). This difference is not very significant, just as with the wall support sections.

Projected width of the section. Figure 15 indicates the projected widths of all the simulated sections, differentiated by the way the glazing is fitted. A correlation is seen between both variables: the width is higher for the offset setup, intermediate for the contained glazing, and lower for the systems with glued glazing. In this way, the differences between these three categories are seen, which also have uneven thermal performances, both in the wall support sections and in crossbeams (parameters 2 and 5).

THERMAL TRANSMITTANCE OF THE FAÇADE

The analysis of the variants of profile designs and their impact on the thermal transmittance values presented in the previous section, allowed determining which parameters are relevant to establish thermal transmittance ranges of glass skin façade systems.

Regarding the column length in wall support sections, the values are kept in a range of around ± 0.6 W/m²K to the value of the setup with a middle column (P2), as such this profiling section is used as follows. The two existing crossbeam design variants (parameter 4) added to this, had the same thermal transmittance values, as such variant T1 was discarded.

It stood out that the sections -both crossbeams and wall supports- with contained glazing, obtain higher thermal transmittance values than sections with glued glazing. Among these categories, whether the glazing is single or double (SG/HDG) and the way of opening the glazed panel (FP/MP), has an impact. In response to this, on one hand, an additional wall support section with contained HDG (P8) is simulated. And, on the other, to simplify analysis, the thermal transmittance values of the variants with FP and MP are averaged, considering that, in a façade setup with fixed sill and lintel and intermediate mobile panel, the two crossbeam variants are used simultaneously.

Although the offset HDG only produces a slight increase of heat transfers (between 0.11 and 0.42 W/m²K) compared to the glued HDG, the 30% increase of the wall support projected width is added to this, all of which

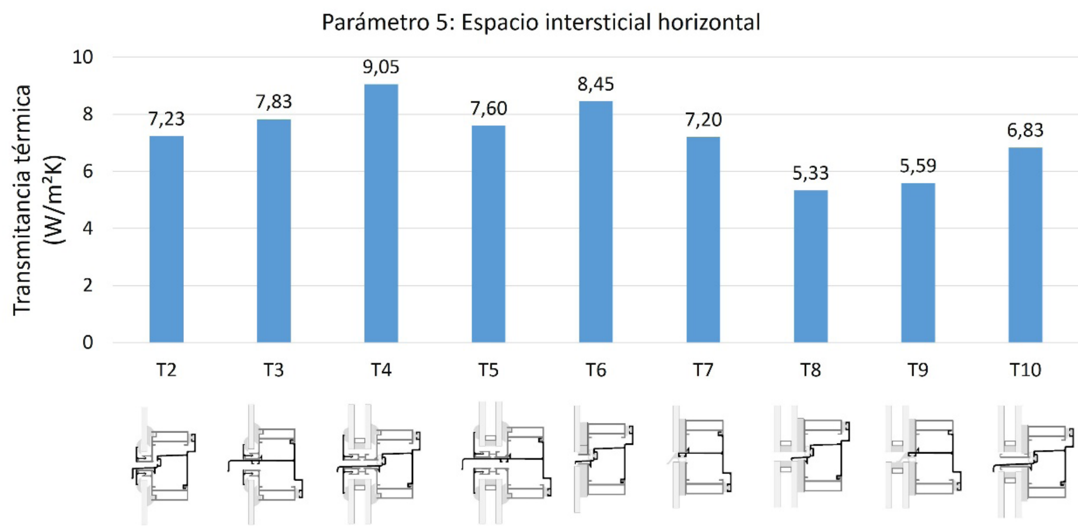


Figure 13. Effect of the horizontal interstitial space on the thermal transmittance value. Source: Preparation by the Authors.

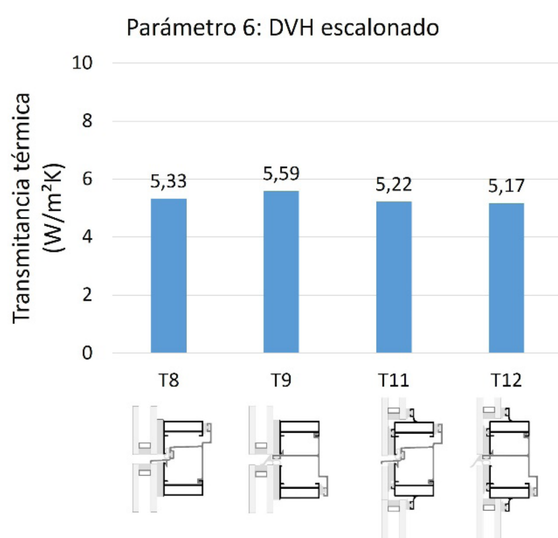


Figure 14. Effect of the offset HDG on the thermal transmittance value of the crossbeam. Source: Preparation by the Authors.

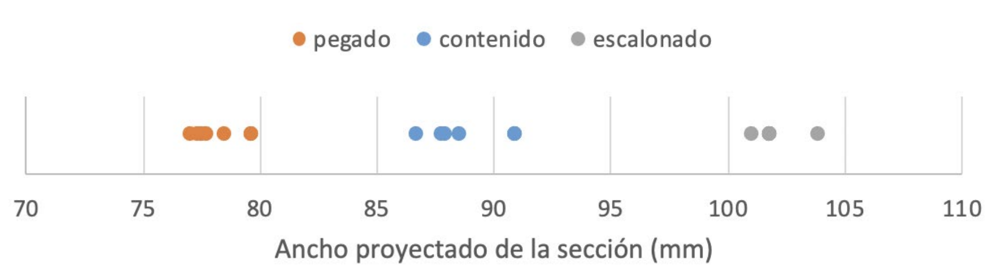


Figure 15. Spread of the projected width values of the sections analyzed, differentiated depending on the type of glazing fitting (glued, contained, and offset). Source: Preparation by the Authors.

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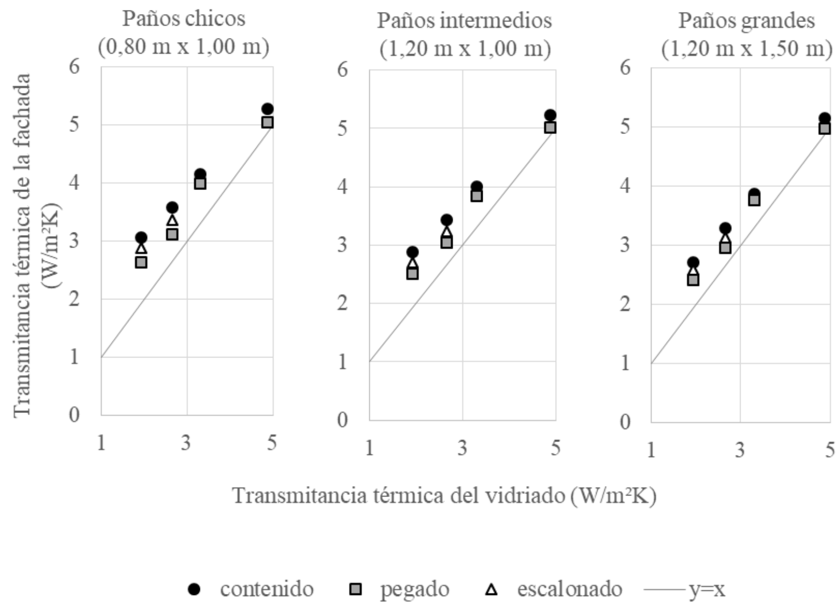

Figure 16. Representation of the thermal transmittance values of façade systems, differentiated by the way of fitting the glazing (glued, contained, and offset) and the sizes of the glazed panels.Source: Preparation by the Authors.

contributes to increase the thermal transmittance value of the whole façade. Therefore, this aspect is analyzed as a separate category.

Figure 16 presents the results of the simulations made, divided into three graphs -one for each façade sizing-, where the thermal transmittance values of the facades are expressed with contained, glued and offset glazing, considering the glazing used. The "identity" function is also graphed, to show the impact of the metal latticework on the total U value of the façade. On average, the U value exceeds the Ug value by 24%.

However, it is seen that the thermal transmittance of the glazing is the most important factor to consider to reach given thermal transmittance value ranges for the entire façade.

The sizing of the glazed panels has a variable impact, with the maximum difference obtained being 13%, which corresponds to the contained G1 glazing, a setup with the highest contrast of thermal transmittances (lowest U_g and highest U_f). On average, a difference of 7% is calculated between the extreme sizes studied.

The means of fitting the glazing has a significant impact in the case of facades with HDG (differences of 11% to 16% between setups with contained and glued glass). The variants with offset HDG have intermediate thermal transmittance values.

CONCLUSIONS

The analysis of the variants of profile designs for glass skin facades allowed isolating several parameters, and then studying the impact of each one on the thermal transmittance values (U_f) of the profiling sections.

The most important parameters identified are the column length and the means of fitting the glazing (contained or glued) in the wall support sections, and the design of the horizontal interstitial space in crossbeam sections, where the type of glazing (SG or HDG) and their means of fitting, as well as the type of opening (FP or MP) are involved.

However, the crossbeam design (Figure 4) is not relevant, and the setup with offset HDG does not significantly change the U_f value compared to the common HDG. However, said setup stands out on having a higher section width than variants with glued or contained HDG, in such a way that it produces a difference in the thermal transmittance of the entire façade system.

Using the information collected in this preliminary study, a more reduced sample of profiles was chosen to make the analysis of entire façade systems. The results indicate that thermal transmittance values of the glass skin facades available in Argentina vary significantly (from 2.42 to 5.28 W/m²K), mainly depending on the thermal transmittance of the glazing, but also in their fitting system (contained, glued, or offset), as well as the sizes of the glazed panels.

The results confirm the importance of having the thermal transmittance data of integrated façade systems, as using an estimate of the thermal transmittance value of the glazing leads to underestimating the thermal flows that will occur through the façade (24% higher on average).

The contributions of this work provide a valuable tool to building designers and constructors, so that decisions can be made not just aiming at economic and constructive criteria, but also from the optic of sustainability.

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ENERGY EFFICIENCY IMPROVEMENTS IN HEATING. POTENTIAL FOR INTERVENTION IN AN EXISTING SCHOOL BUILDING IN THE METROPOLITAN AREA OF SAN JUAN, ARGENTINA.

MEJORAS DE EFICIENCIA ENERGÉTICA EN CALEFACCIÓN. POTENCIAL DE INTERVENCIÓN EN EDIFICIO ESCOLAR EXISTENTE DEL ÁREA METROPOLITANA DE SAN JUAN, ARGENTINA

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RESUMEN

El cambio climático, el constante crecimiento del consumo energético y los altos niveles de emisiones que registra el sector energético, requieren de la implementación de soluciones concretas. La rehabilitación de edificios ofrece una oportunidad significativa para contribuir en este aspecto. El objetivo del presente trabajo es analizar el potencial de intervención en un edificio escolar perteneciente al Programa Nacional 700 Escuelas. Las mejoras en eficiencia energética se evalúan a través de simulación dinámica y se calculan indicadores respecto al consumo anual de energía para calefacción. Los valores para el edificio de referencia son de 74,5 kWh/m2 año y de 158 kWh/alumno. Con las propuestas de rehabilitación se podrían alcanzar ahorros energéticos de entre 39,7% y 60%. La alternativa R-Media se presenta como la más conveniente al lograr beneficios energéticos del 47%, con menores costos de inversión. Los indicadores de eficiencia energética para dicho conjunto de mejoras son de 39,2 kWh/m2 año y de 83,1 kWh/alumno. Los resultados alcanzados pueden servir de referencia para la rehabilitación de 71 edificios escolares erigidos en la provincia de San Juan entre los años 2004 y 2015, los cuales responden a una tipología constructiva con similitudes de materialización de la envolvente y configuración funcional.

Palabras clave
escuelas, rehabilitación energética, eficiencia energía, simulación.

ABSTRACT

Climate change, the constant growth of energy consumption, and the high levels of emissions recorded by the energy sector, require the implementation of concrete solutions. Building rehabilitation offers a significant opportunity to contribute in this regard. The purpose of this work is to analyze the potential for intervention in a school building from the "Programa Nacional 700 Escuela" (National 700 Schools Program). The improvements in energy efficiency are evaluated through a dynamic simulation and indicators are calculated regarding the annual energy consumption for heating. The values for the reference building are 74.5 kWh/m2 year and 158 kWh/student. With the rehabilitation proposals, energy savings could be achieved of between 39.7% and 60%. The R-Mean alternative appears as the most convenient one as it achieves energy benefits of 47%, with lower investment costs. The energy efficiency indicators for said set of improvements are 39.2 kWh/m2 year and 83.1 kWh/student. The results achieved can serve as reference for the rehabilitation of 71 school buildings built in the province of San Juan between 2004 and 2015, which belong to a construction typology with a similarity of materials of their envelope and functional configuration.

Keywords
schools, energy rehabilitation, energy efficiency, simulation

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INTRODUCTION

The construction industry and building operation have the highest share in energy use and associated carbon dioxide emissions. During 2017, they represented 36% of final energy consumption, with a CO_2 production of 39% (IEA, 2018). Currently, there is a growing interest of countries in their state policies, to improve the performance of the building sector. In Argentina, the IRAM 11900 Standard (2017) constitutes progress in regulatory matters, although it is limited to residential use.

The energy retrofitting of buildings can be achieved by applying bioclimatic design strategies, improving the thermal properties of the envelope, replacing equipment for more efficient ones, and using passive or hybrid climate control systems that involve renewable energies (Esteves, 2017). Likewise, improvements of vertical and horizontal enclosures, with the incorporation of insulation materials, represent an investment in the quality of the infrastructure (Andersen, Discoli, Viegas & Martini, 2017; Camporeale, Mercader y Czajkowski, 2017; A. Esteves, M. Esteves, Mercado, Barea & Gelardi, 2018, Kuchen & Kozak, 2020).

The intervention potential for school building envelopes generates a two-fold benefit: improving energy efficiency and optimizing thermal comfort levels. Schools must guarantee indoor environmental quality standards, so that students and teachers can properly experience teaching-learning processes (San Juan, 2014, Barbosa, De Freitas & Almeida, 2020).

Energy efficiency in buildings is measured using consumption units per area (kWh/m^2 year). This indicator allows making comparisons at a domestic and international level. However, for school buildings it has shortcomings, like the exclusion of usage. Schools comprise, as is well known, spaces with diverse characteristics. The energy consumption must also be defined considering the occupation of spaces (kWh/student). On adopting a combination of both energy efficiency indicators, a more complete image is obtained (Sekki, Andelin, Airaksinen & Saari, 2016). In particular, one study in Brazil (Geraldi & Ghisi, 2020) determined that the energy use intensity indicator considering the number of students, is more reliable and suitable to represent the stock of school buildings.

The energy behavior assessment of existing buildings and retrofitting proposals, can be addressed using different complementary approaches (Wang, Yan, & Xiao, 2012). In this sense, dynamic simulation is a favored tool to analyze building operation in their post-construction stage, as it provides the possibility to identify the different parameters that affect energy consumption and quantify their impact on the total values (Veloso & Souza, 2019).

Given this context, the main purpose of this work is to assess energy wise, the intervention potential of a traditional school building, located in the Metropolitan Area of San Juan (AMSJ, in Spanish), using a dynamic simulation. The specific goals seek, first of all, to generate the thermal-physical model of the building, starting from the calibration with the measured energy consumption values; and second, studying different technological and solar energy collector proposals, to reduce energy consumption while keeping comfort; and, third, calculating Energy Efficiency Indicators (EEI).

METHODOLOGY

Work is done based on an applied research, progressing through a case study. A large part of existing school infrastructure, appears as an opportunity to reverse the environmental issue of energy use, if considered as networks instead of independent entities (Boutet, Hernández, Jacobo, 2020). For this study, a representative school building is chosen due to its operational setup and construction technology (Ré, 2017): the Provincial School of Rivadavia (CPR, in Spanish), is part of the National 700 Schools Program (PN700E, in Spanish), valid between 2004 and 2008, and extended through the More Schools (Más Escuelas) program, to 2015. In the Province of San Juan, 71 public schools, which have been built within the framework of these programs, could have energy retrofitting.

The analysis is made in the cold season, on being a critical period for climate control in a school building, given its greater use. Considering the diagnosis, different energy efficiency improvement proposals are made and their assessment is made through a dynamic simulation using the Ecotect software (Autodesk, 2011).

The existing building in its original envelope, equipment and behavior conditions, is called "reference building". This expression is used internationally in stock research and energy retrofitting proposals (Attia, Shadmanfar & Ricci, 2020; Geraldi & Ghisi, 2020).

CLIMATE CHARACTERIZATION AND LOCATION

The city of San Juan is located at 640 masl, and its geographic coordinates are: 31°32'13" S 68°31'30" W. It belongs to the bioenvironmental III-a warm template zone, according to the classification of the IRAM 11603 Standard (2012) for the Republic of Argentina (Table 1). Subzone "a" has daily and

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Climate data		Unit	Winter	Summer
Temperature	Mean	°C	10,61	25,56
	Max. Mean		18,5	33,1
	Min. Mean		2,7	18
	Design Max.		-	41,4
	Design Min.		5,6	-
Relative humidity		%	58	46,7
Rainfall	Mean	mm	13	60,2

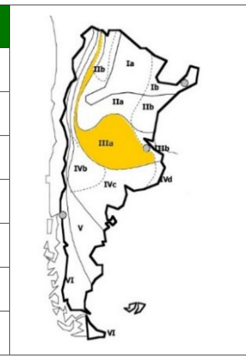

Table 1. Climate data of San Juan. Maps of the geographic location and Bioenvironmental Zone III.a. Source: Preparation by authors based on data from IRAM 11603 Standard (2012). Map: Wikipedia (2020).

Variable	Un.	January	February	March	April	May	June	July	August	Sept	Oct	Nov	Dec
Mean T°	°C	26,49	26,46	21,59	19,53	15,37	13,16	9,82	12,75	13,88	21,28	23,92	28,09
Max T°	°C	31,34	31,71	26,25	24,62	20,57	18,31	14,75	18,88	19,35	26,64	29,65	33,23
Min. T°	°C	21,36	21,16	16,89	14,33	10,41	7,83	5,09	6,76	8,51	15,60	17,91	22,47
Relative humidity	%	45	37	46	46	47	38	44	32	37	34	32	36
Solar Radiation	W/m2	311	320	248	206	153	125	126	166	200	281	324	355
Atmospheric pressure	kPa	93,73	93,60	93,90	93,94	93,98	94,12	94,27	94,26	94,22	93,81	93,64	93,47
Wind speed	m/s	2,85	2,96	2,99	2,00	2,10	1,94	2,14	2,39	2,99	3,06	3,26	3,32
Dew point	°C	12,60	10,18	8,54	6,93	3,40	-1,67	-2,69	-4,78	-1,42	3,14	4,48	10,55
Wet bulb T°	°C	26,37	25,79	20,66	18,56	14,21	11,02	7,82	10,66	12,07	19,69	22,31	27,36

Table 2. Monthly average climate variables of 2013. Source: Preparation by authors based on the data of Pontoriero (2017).

seasonal thermal amplitudes, that are equal or greater than 14°C.

A climate file of the year under study was prepared to simulate the energy performance of the school building, which allows a closer approach to reality. The information was processed and transcribed into the Elements program (Rocky Mountain Institute [RMI], 2020). The climate data of San Juan was obtained with a meteorological station located in the Electricity Institute (Pontoriero, 2017). Table 2 shows the information input into the program.

CASE STUDY

The Provincial School of Rivadavia is a state-run secondary school. The school has a ground floor, with a covered surface area of 1169.4 m^2 and a heated surface of 604.38 m^2. The circulation areas are semi-covered, using corridors. The construction technology is baked large brick masonry walls, with 30 cm or 22 cm bonds, and plaster on the outside. The upper horizontal enclosure is made from reinforced flat or sloped concrete slabs, with a tile finish (classroom sector). It has sliding woodwork, of a steel sheet frame and single glazing. The windows have north and west facing shutters (Figure 1).

In the diagnosis stage, the shading range is analyzed from 9am to 5pm, every 30 minutes, for June 21st, with the goal of studying the potential solar gain that the building has (Figure 2). The classrooms (all north-south facing), have crossed ventilation and natural lighting. However, the north-facing shutters restrict entry of sunlight in winter, on remaining relatively closed most of the time.

The thermal-energy assessment of school buildings significantly differs from other uses and merits considering other aspects, like:

- Occupation: 285 students spread over the morning and afternoon sessions.
- Maximum gross occupation density per classroom and per session: 2.29m^2/student; value that corresponds to 24 students per 55m^2 classroom.
- Ventilation rate per classroom, as per ANSI/ ASHRAE Standard 62.1 (2019): 551m^3/h. classroom or 23m^3/h.student
- Building use time: 8 h from Monday to Friday; 6 h on Saturday.

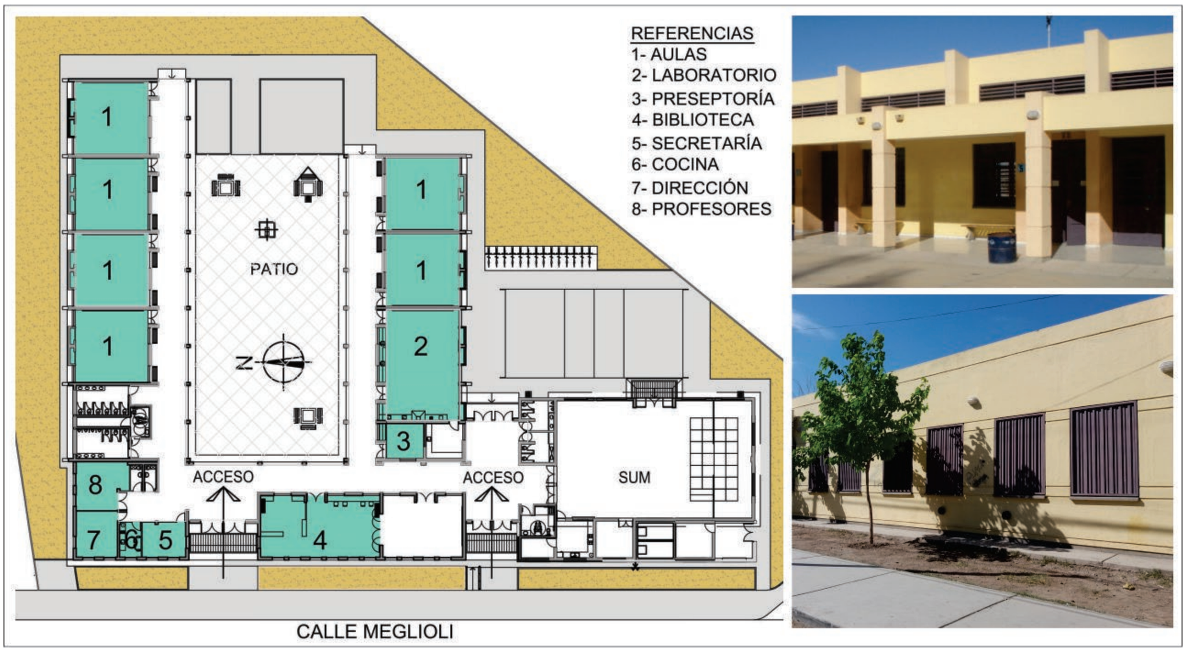

Figure 1. Floor plan of CPR, with identification of spaces with mechanical heating (in green). Photographs of the corridor and front of the building with the shutters. Source: Preparation by the authors.

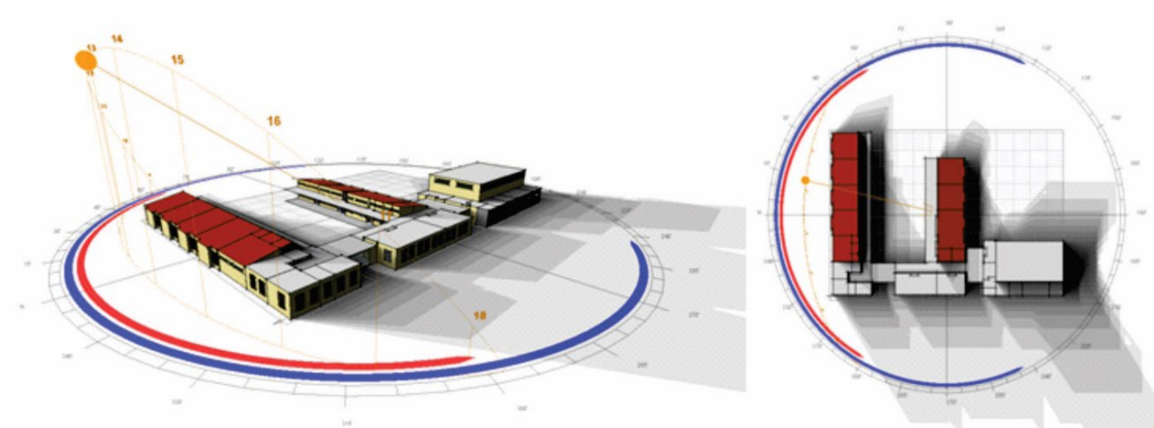

Figure 2. Building volumetry. Shading analysis for June 21st. Source: Preparation by Authors with Ecotect.

DYNAMIC ASSESSMENT

The reference building and the different retrofitting proposals are evaluated using dynamic simulation with Ecotect . The software makes the comprehensive and simultaneous analysis of sunlighting, internal gains, geometric and construction elements technological setup, possible. Ecotect allows studying the intervention potential of construction solutions by modifying the existing condition, and individualizing different areas of the building to get to know their energy performance. Different authors who currently use the program, have concluded that the results obtained are fair, considering the data measured and simulated (Trisnawan, 2018; Khan, Asif & Mohammed, 2017; Harish & Kumar, 2016).

To provide reliability and validity to the simulation results, the calibration of the IT model was done using empirical data (Godoy-Muñoz, 2015). The electricity and natural gas consumption records of the school

1 ECOTECT used a simplified calculation based on the Admittance Method of the Chartered Institute of Building Services Engineers (CIBSE Admittance Method). It applies the admittance of construction elements and thermal attenuation and delay factors of materials to define the transitory system.

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Heating energy consumption							
Two-month period	1	2	3	4	5	6	Anual
Natural Gas Consumption							kWh
Cooker/Oven	292	667	697	712	622	508	3498
Heating (VF heaters)	11	3630	19491	13714	7719	_	44565
Total Gas	303	4297	20188	14426	8341	508	48063
Electricity Consumption							
Quartz Space Heater	_	68	141	95	_	_	304
Heating Fans	_	185	378	251	_	_	814
Electrical heating	_	253	519	346	_	_	1118
Other uses	7412	10026	7007	7597	6280	6266	44588
Total Electricity	7412	10279	7526	7943	6280	6266	45706
Total Heating	11	3883	20010	14060	7719	_	45683

Table 3. Natural gas and electricity consumption of the building. Heating consumption discriminated by energy source. Source: Preparation by the Authors.

corresponding to the energy audit of 2013 were used (Ré, Blasco Lucas y Filippín, 2016).

The climate control system adopted for the simulation is "heating only" in the rooms with heaters, and "full air-conditioning" for the space that has a split Air Conditioning (AC) unit.

ENERGY CONSUMPTION

The energy analysis focused on the building's operation phase (operative energy). The consumption data was obtained from service bills and the energy audit. The natural gas records, in m^3, are converted into kilowatt hours (kWh). A conversion factor of 9,767 kWh/m^3 is used, which comes from considering the Lower Heating Value of the natural gas (8400 $kcal/m^3$) and an equivalent of 1 kW to 859.9 kcal/h (Selectra, 2020).

The electrical equipment for climate control the school has is: 2 heating fans (1500 W), 1 quartz space heater (1200 W) and 1 AC (2150 W) in the administration sector. In the classrooms, there are wall fans (90 W). The natural gas heating devices are 10 vent-free gas heaters of 5700 kcal/h and 4 of 3800 kcal/h.

Gas consumption for heating is 44,565kWh/year. The electricity used to heat the rooms is calculated at 1,118 kWh, according to the power and hours of use of devices (ENRE, 2020). Table 3 shows each consumption by two-month period, using the information from the service bills.

RETROFITTING PROPOSALS

Using what has been seen, energy retrofitting proposals for the school building are prepared as thermal-energy behavior optimization measures. These involve: increasing the area of direct solar gain (DSG) in the classrooms on the north corridor; increasing the thermal resistance of the envelope; and efficiency improvements in the mechanical climate control system.

The increase of the collector area is applied to the north corridor classrooms due to their potential for intervention. The values reached represent 13% of the effective glazed area compared to the useful area of the classroom. The windows pass from 5.15m^2 (reference building) to 7.04m^2 (rehabilitated case). In addition, the decision was made to eliminate the shutters on this side, so that solar gains are not reduced in winter.

The thermal properties of the vertical and horizontal enclosures are calculated using the procedures of the IRAM 11601 Standard (2002). The improved elements confirm the thermal transmittance values suggested in IRAM 11605 (2002) in comfort levels A – *recommended* and B – *medium*. An External Thermal Insulation System (ETIS) is used for wall retrofitting. The existing woodwork is replaced by doors and windows that allow increasing the effective glazed area, improving thermal properties, and reducing air infiltrations. The substitution is foreseen in all the heated spaces of the building. At level A, aluminum frames are used with a thermal bridge breaker (TBB) and hermetically sealed double glazing (HDG 6-12-6 mm). In level B, a simple frame with HDG is used.

The construction improvements are grouped into different intervention proposals, which have the following names: Simple Retrofit (Simple-R) A and B, Medium Retrofit (Medium-R) and Optimal Retrofit (Optimal-R). Table 4 shows the makeup of each group,

Technological Component	Properties	Reference Building	Simple-R B	Simple-R A	Medium-R	Optimal-R
Woodwork		Sheet metal	Aluminum	Aluminum + TBB	Aluminum	Aluminum + TBB
	Material	V. Simple (6 mm)	DVH (6-12-6 mm)	DVH (6-12-6 mm)	DVH (6-12-6 mm)	DVH (6-12-6 mm)
	U [W/m2.K]	5.66	3.89	2.82	3.89	2.82
Wall 1	Material	Brick + plaster	Brick + plaster	Brick + plaster	EPS 50 mm + plaster	EPS 100 mm + plaster
	Thickness [cm]	30	30	30	35	40
	U [W/m2.K]	2.04	2.04	2.04	0.49	0.28
Wall 2	Material	Brick + plaster	Brick + plaster	Brick + plaster	EPS 50 mm + plaster	EPS 100 mm + plaster
	Thickness [cm]	22	22	22	27	32
	U [W/m2.K]	2.47	2.47	2.47	0.51	0.28
Sloped slab	Material	Slab H° A°+ mix + tiles	EPS 100 mm + galvanized sheet	EPS 150 mm + galvanized sheet	EPS 100 mm + galvanized sheet	EPS 150 mm + galvanized sheet
	Thickness [cm]	30 cm	40.2	45.2	40.2	45.2
	U [W/m2.K]	1.35	0.26	0.18	0.26	0.18
Flat slab	Material	Slab H° A°+ mix + membrane	EPS 100 mm + mix + membrane	EPS 150 mm + mix + membrane	EPS 100 mm + mix + membrane	EPS 150 mm + mix + membrane
	Thickness [cm]	26 cm	39 cm	44 cm	39 cm	44 cm
	U [W/m2.K]	1.43	0.26	0.18	0.26	0.18
U Global [W/m2.K]		**2.26**	**1.54**	**1.35**	**0.98**	**0.71**

Table 4. Technological components. Materials, thermal properties. Reference building and retrofitting proposals. Source. Preparation by the authors.

with their respective thermal transmittances (U). For air renewals, a rate of 2.6 is considered, the value established to guarantee healthy hygienic conditions (ANSI/ASHRAE, 2019).

The investment costs and Amortization Period (AP) are also analyzed, aspects that contribute in decision making. Said estimation could have significant variations in the future due to the high inflation seen in the country over the last decade, and likewise, on facing possible changes in government policy for energy subsidies, a situation that is currently happening.

The third strategy is improving the heating system efficiency. The replacement of individual equipment is proposed (vent-free heaters) that have an efficiency of 59%, according to the IRAM 11900 Standard (2017), with a central heating system whose estimated efficiency is 65%.

The savings potential is analyzed using two Energy Efficiency Indicators: kWh/m^2 year and kWh/student, for the total of the heated building (604.38m^2), and for the 4 classrooms on the north corridor (200m^2). The number of students is 285 and 192, respectively.

RESULTS AND DISCUSSION

Figure 3 presents the calibration of the reference case's computation model using the energy records. The real heating energy consumption is compared with the values calculated in the simulation. The scatter graph shows a R^2 = 0.956 ratio, which is statistically significant ($P \leq 0.05$). It is considered that the model obtained can be used to study the behavior of the different technologies proposed.

2-month period	Data measured	Data simulated
	Heating consumption (kWh)	
1 (feb-mar)	11	1.479
2 (apr-may)	3.883	5.191
3 (jun-jul)	20.010	21.367
4 (aug-sep)	14.060	15.722
5 (oct-nov)	7.719	1.259
Total	45.683	45.018

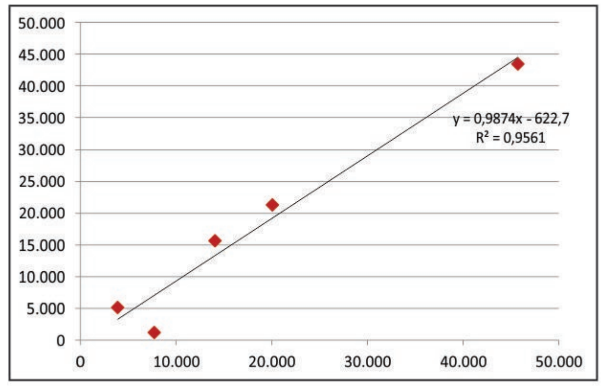

Figure 3. Energy consumption for heating. Data measured in 2013 vs. simulated. Source: Preparation by Authors.

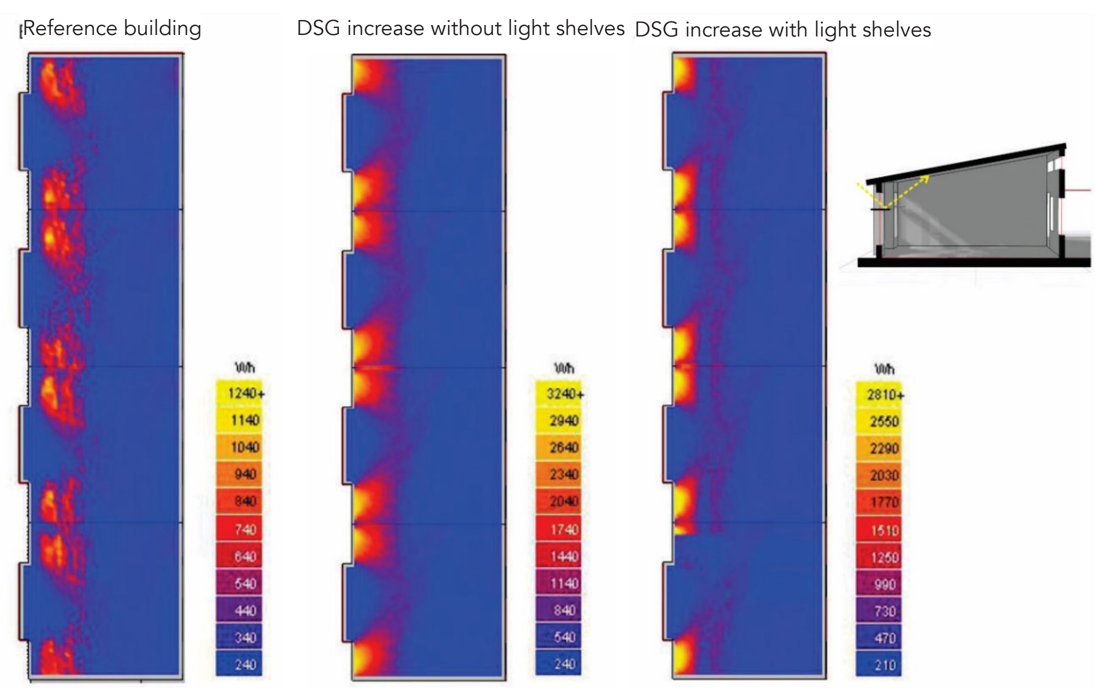

Figure 4. Impact of average daily radiation on north corridor classrooms. Reference building and Optimal-R. Source: Preparation by the Authors with Ecotect.

ENERGY EFFICIENCY IMPROVEMENTS

In north-facing classrooms, the average daily radiation in winter is analyzed on a work plane located 80 cm from the ground (Figure 4). In the image on the left, the windows of the reference building with open shutters can be seen. In the center, the Optimal Retrofit with an increase of the direct solar gain surface and removal of the shutters. In order to mitigate glare, fixed light shelves are placed, which generate a uniform distribution in the classroom space (Figure 4, right); and to avoid undesirable heat gains, an eave is generated with the sloped roof, which provides shading in warm months.

Possible overheating in summer is evaluated through the simulation. Thus, the cooling energy consumption calculation is made for the 4 classrooms being worked on, with a system efficiency of 3.6 according to the IRAM Standard (2017). The results show a consumption of 3,871 kWh/year for the reference building during the summer period (from October to March). The retrofitted cases would consume 3,338 kWh/year Optimal-R, and 3,360 kWh/year Optimal-R + DSG, confirming that the mechanical climate control requirement is not increased.

The heating energy consumption for the reference building, and for the different retrofits can be seen in Figure 5. The EEI for each case can be seen on the same graph. The consumptions simulated with the existing vent-free (VF) heaters are represented in blue, and the central heating (CH) system, in green.

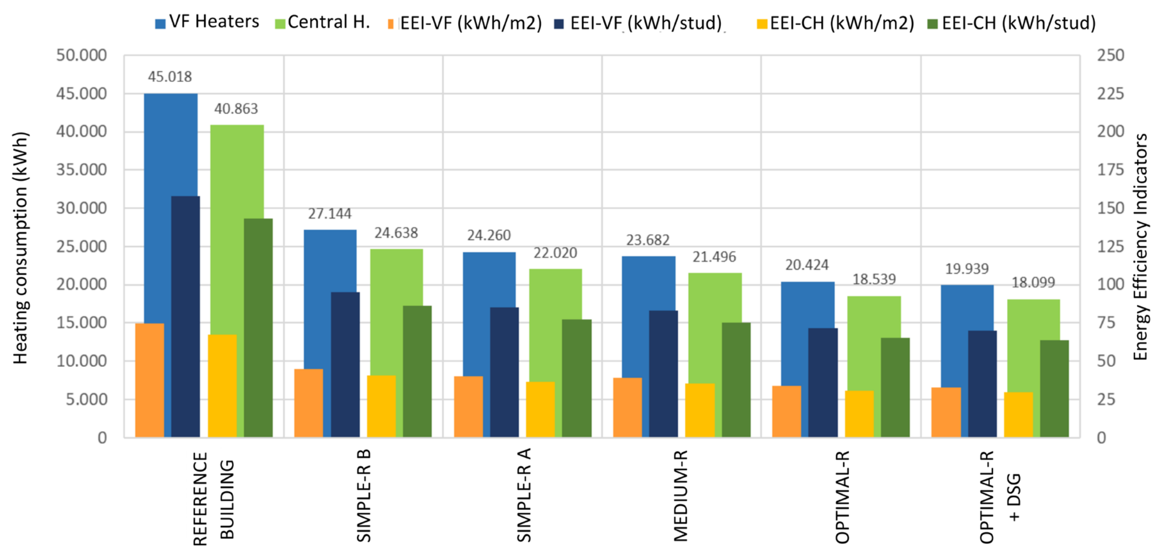

Figure 5. Heating energy consumption for reference building and retrofit proposals. Source: Preparation by the Authors.

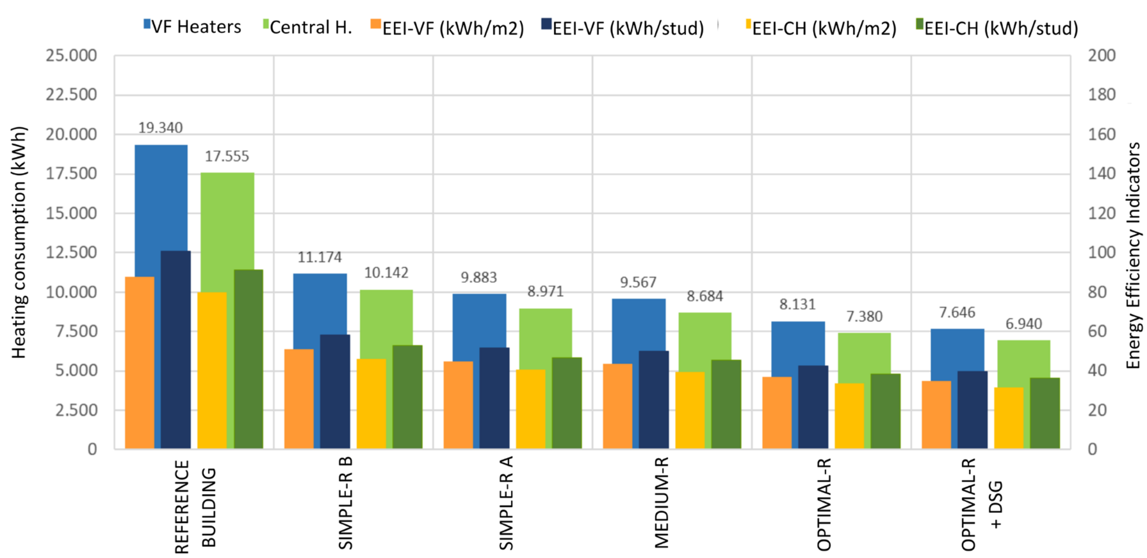

Figure 6. Heating energy consumption of the north corridor classrooms sector. Source. Preparation by the Authors.

The reference building reduces its consumption from 45,018 kWh/year to 40,863 kWh/year with a change of equipment, representing a saving of 9%.

With the increase of the envelope's thermal resistance, the energy consumption falls from 27,144 kWh/year (Simple-R B-VF) to 18,539 kWh/year (Optimal-R-CH). The EEI-VF for these cases is 44.0 kWh/m^2 and 95.2 kWh/student, and EEI-CH is 30.7 kWh/m^2 and 65.0 kWh/student. The Optimal-R model with an increase of the Direct Solar Gain (DSG) and central heating system, shows an energy performance of 18,099 kWh/year with a consumption reduction of 60%. In this proposal, the EEI falls from 74.5 kWh/m^2 and 158 kWh/student (reference building) to 29.9 kWh/m^2 and 63.5 kWh/student.

The intervention potential of the four north-facing classrooms can be seen in Figure 6. This zone could reduce its consumption from 19,340 kWh/year to 6,940 kWh/year, if the 3 proposed strategies were applied. The EEI range from 87.9 kWh/m^2 and 100.7 kWh/student (EEI-VF Reference Building) to 31.5 kWh/m^2 and 36.1 kWh/student (EEI-CH Optimal-R + DSG). The Energy Efficiency Indicators per student for the classroom sector have significantly lower values than

Variant analyzed	EEI-VF	EEI-VF	Consumption	Cost per year	Value/surf	Total Retro	Total Retro	Amortization
Case	kWh/m2	kWh/alumno	kWh/año	$	U$/m2	U$	$	Años
Ref. building	74,5	158,0	45.018	52429				
Simple-R B	44,9	95,2	27.144	31613	108	65.296	6.298.848	55
Simple-R A	40,1	85,1	24.260	28254	153	92.301	8.923.369	67
Medium-R	39,2	83,1	23.682	27581	127	76.953	7.406.979	54
Optimal-R	33,8	71,7	20.424	23787	182	109.787	10.614.726	67
Optimal-R+DSG	33,0	70,0	19.939	23222	191	115.364	11.132.611	69

Table 5. Comparison of EEI, energy costs, and value of the investment for the envelope retrofit proposals. Dollar US$1 = $96.5 at 26/05/2021, Banco Nación Argentina. Source: Preparation by the Authors.

National 700 Schools Program in AMSJ	EEI - surface	EEI - density
Units of analysis	kWh/m2	kWh/student
Escuela Técnica Obrero Argentino	32,2	81,6
Escuela Provincial Educación Técnica N°5	33,6	101,0
Colegio Provincial de Rivadavia	75,6	160,3
Colegio Secundario Jorge Luis Borges	24,9	61,6
Colegio Superior N°1 Rawson	28,2	35,5

Table 6. EEI of Schools belonging to PN700E of the Metropolitan Area of San Juan. Source: Preparation by the Authors.

those for the entire building. These represent the differentiated use intensity that characterize school typology buildings.

The improvements proposed are analyzed below from the economic aspect. The consideration of the investment costs per surface unit (US$/m^2) and the Amortization Period help in the decision making. The comparison of the EEI with the AP allow identifying that the Simple-R B and Medium-R improvements are the most suitable to allow reducing energy consumption with a moderate investment (Table 5). The Optimal-R + DSG has the greatest energy saving, but has high construction values (US$191/m^2), conditioned by the cost of the technological components. The aluminum windows with TBB, double the value of those that do not have them. The alternative Medium-R reduces the energy demand by 47%, with investment costs of US$127/m^2. The heating energy consumption indicators for this set of improvements are 39.2 kWh/m^{2}year and 83.1 kWh/student.

It is warned that the AP is higher in the number of years, due to the low energy costs at a national level, where both natural gas and electricity are subsidized. In addition, their value did not match the significant increase in annual inflation seen in recent years. However, the energy efficiency improvements proposed in this work are justified from an environmental and social point of view, within CO_2 emissions reduction policies, and indoor thermal comfort improvements during the building's service life. It is considered that, in school typologies, where the education and training of future generations takes place, that the suitable conditions of the classroom, and the reduction of the energy demand, exceed the business vision regarding the return on investment.

HEAT LOSSES AND GAINS

The energy losses through opaque enclosures and openings, for a typical day in July are also analyzed using the simulation software. The heat losses through convection and air infiltration between the Reference Building and Optimal-R are compared. The study reveals that the proposed improvements achieve a reduction of 29.2% and 37.6%, respectively.

Regarding thermal gains, it is seen that the increase of the collector area in the north-facing classroom sector represents a contribution of 6%. The internal loads (people, lighting, equipment) show a heat contribution of between 56% and 61% in the retrofit proposals.

ENERGY EFFICIENCY INDICATORS

The EEI of CPR, are compared with the energy behavior that other school buildings of the PN700E located in the Metropolitan Area of San Juan, show. The data of Table 6 express the energy consumption indicators by surface unit and by student, calculated based on real records obtained from service bills. It can be seen that the school analyzed has the highest values, which justifies the need for retrofitting.

The results attained in this study could be transferred to improve the energy performance and the indoor thermal comfort conditions of other school infrastructure from the national programs implemented in the province between 2004 and 2015.

CONCLUSION

The work presented allowed analyzing the intervention potential of different retrofitting proposals. Concretely, the Optimal-R + DSG incorporates improvements in the thermal transmittance of the envelope (Global U of 0.71 W/m²K), direct solar gain in north-facing classrooms, and efficiency of the heating system. This set verifies the Level A defined by IRAM 11605 (2002), and reduces the energy consumption by 60% compared to the reference building. The Medium-R, with Global U values of 0.98 W/m²K, attains Level B of the Standard, and shows potential energy savings of 47% compared to VF heaters. Said proposal is the most convenient alternative after comparing potential energy consumption, investment costs, and the amortization period.

The energy efficiency indicators calculated for the retrofitted building, give an annual heating energy consumption range from 44.9 kWh/m²year to 33 kWh/m²year and of 95.2 kWh/student to 70 kWh/student. The values for the reference building are of 7.45 kWh/m² year and 158 kWh/student, in the simulation model.

The data allow acknowledging the importance of considering gains from radiation and internal ones in densely occupied spaces like school classrooms, for a better approximation to the auxiliary annual heating load value, in analytical calculations and of a seasonal system.

Facing the new reality brought on by the Covid-19 pandemic, and facing possible epidemics that involve climate control regarding disease transmission, ASHRAE (2020) recommends, in the case of schools, to increase classroom ventilation with a suitable outside air supply, that allows diluting contaminants. This situation encourages the scientific sector to perfect considerations on energy consumption.

Likewise, considering the new health demands in school buildings, the need is clear to revise and update the School Architecture Basic Regulations and Criteria (Ministry of Education, 1998). Among the different aspects that merit being checked, the recommended values for air renewals and room ventilation are highlighted, as these directly affect people's health.

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TUHOUSE: SUSTAINABLE, HIGH-DENSITY SOCIAL HOUSING PROTOTYPE FOR THE TROPICS

TUHOUSE: PROTOTIPO DE VIVIENDA SOCIAL SOSTENIBLE DE ALTA DENSIDAD PARA EL TRÓPICO

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RESUMEN

La presente contribución expone los resultados de la investigación desarrollada en el marco del concurso internacional Solar Decathlon LAC 2019, la cual tuvo por objetivo el diseño y construcción de un prototipo de vivienda económica TUHOUSE (Technically Unique House Using Solar Energy), a escala 1:1, capaz de incorporar estrategias sostenibles y bioclimáticas acordes con la región tropical. Para esto se llevó a cabo una metodología de taller de diseño, basada en el trabajo interdisciplinario entre distintas áreas de la Arquitectura y la Ingeniería, pertenecientes a diversos programas de las Universidades de San Buenaventura y Autónoma de Occidente (Cali, Colombia). El principal aporte metodológico fue lograr aquel trabajo interdisciplinario desde las etapas iniciales, lo cual se suma a que estudiantes y profesores participaran en la construcción del prototipo para finalmente verificar su comportamiento con las pruebas del concurso. Entre resultados de la experiencia, se destaca la propuesta urbana con alta habitabilidad y densidad, y la comprobación de estrategias pasivas de diseño enfocadas en la envolvente del prototipo, que pueden ser replicadas en condiciones similares, pero también la importancia del interrogante sobre la validez del modelo de confort térmico propuesto para regiones tropicales.

Palabras clave
vivienda social, prototipo, sostenibilidad, bioclimática, trópico

ABSTRACT

This work presents the results of research made within the framework of the Solar Decathlon LAC 2019 international competition, which aimed at designing and building a prototype of a TUHOUSE (Technically Unique House Using Solar Energy) affordable dwelling, at a 1:1 scale, a house that is capable of incorporating sustainable and bioclimatic strategies for the tropical region. The methodology consisted of a design workshop with interdisciplinary work from the different architecture and engineering areas in programs at the Universities of San Buenaventura and Autonoma de Occidente (Cali, Colombia). The main contribution of the methodology was to achieve interdisciplinary work from the initial stages, alongside students and teachers participating in the construction of the prototype, before finally checking its performance using the contest's tests. Among the results that stand out from of this experience, are an urban proposal with high habitability and density, the testing of passive design strategies focused on a prototype envelope that can be replicated in similar conditions, but also the importance of the question about the validity of the thermal comfort model proposed for tropical regions.

Keywords
social housing, prototype, sustainability, bioclimatic, tropics

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INTRODUCTION

The TUHOUSE prototype is the result of an academic reflection on the role social housing has in the makeup of the residential habitat, and their commitment with improving the environment and the different life quality aspects. TUHOUSE proposes a replicable, flexible social housing model, that is adaptable to different contexts, and to different neighborhoods. The concept of sustainability and bioclimatic strategies are directly related to urban-architectural decisions, in the means that the proposal incorporates sustainability criteria, implementing urban agriculture and composting systems in common spaces, thus favoring the formation of community, and contributing towards generating food security and additional income for the families.

The buildings are proposed in a structural and construction system using large pre-fabricated Recycled Concrete Aggregate (RCA) pieces, which look to substitute the use of non-renewable raw materials, and to reduce the impact of Construction and Demolition Waste on the landscape (Bedoya & Dzul, 2015). In Colombia, a variety of materials are used to build terraced social housing, 99% of which are based on high density masonry, like concrete (Giraldo, Czajkowski & Gómez, 2020).

Understanding social housing as the most prized possession of the inhabitants, it has to solve socio-cultural needs: providing shelter (considering the different ways of life and customs), being able to be transformed to house different kinds of families, and their growth, and being durable (housing is for life, it is the legacy of the family). But it must also consider needs of an economic nature: valuation of the dwelling, profitability and generation of extra income, among others.

Apart from the commitments inherent to the area, nowadays Architecture also has commitments with care for the environment, conservation of the planet, energy efficiency, and comfort. However, some social housing in Cali has poor landscaping and lacks bioclimatic strategies, reaching temperatures of up to 49°C inside (Gamboa, Rosillo, Herrera, López & Iglesias, 2011), and thus, a high discomfort for their inhabitants. As Montoya (2014) says, in general the projects have limited typology exploration and deficient conditions regarding their solar orientation, their protection elements in common spaces, and their facades and roofs. Unfortunately, in most of the current projects, a limited implementation of bioclimatic and sustainable strategies is seen, such as the right orientation, shading on the façade, natural ventilation, which are reserved for a few dwellings among the more favored economic sectors of the population.

The residential sector also consumes around 20% of the country's total energy (Energy Mining Planning Unit [UPME, in Spanish], 2019), and from this consumption, depending on the economic conditions, between 40% and 60% is destined for climate control through air conditioning, cooling, and the use of fans (UPME, 2018).

The TUHOUSE prototype was built by students and professors, at a 1:1 scale, within the 2019 Solar Decathlon contest for Latin America and the Caribbean (LAC), and considers the lessons learned by the team in the previous version in 2015 with the MIHOUSE prototype. In said prototype, the architectural and bioclimatic exploration of concrete as an envelope material began (Cobo, Villalobos & Montoya, 2019), along with the first tests on use and reuse of water, waste management through homemade compost heaps, and the incorporation of solar energy using solar panels on the roof (López & Holguín, 2020). This allows presenting to the general non-scientific public, possible alternatives to be included, extending the role of academia outside the boundaries of the University. In this sense, it is worth adding that the project generates alliances not just between universities, but with the public and business sectors.

Therefore, it is pertinent in this revision, to refer to the so-called adaptive thermal comfort model proposed by the international ASHRAE standard in its latest version (ASHRAE/ANSI) for naturally ventilated buildings. This model, led by authors like Auliciems (1975) and Nicol, Humphreys & Roaf (2012), which is based on the average room temperature of a place, emerges as a critique to the ranges established under controlled conditions, part of the analytical model promoted by ASHRAE (ASHRAE, 2005), and revisited for Colombia in NTC 5316 (Colombian Institute of Technical Standards and Certification -ICONTEC, 2004). The analytical model emerges from laboratory run research in contexts with the four seasons (Fanger, 1972; Fanger & Toftum, 2002), which is why its revision in other contexts is needed, like tropical ones (Herrera and Rosillo, 2019), just as seen in recent studies in schools in the tropics (Zapata *et al.*, 2018)

The sustainable and bioclimatic aspects of the proposal are presented below, along with an analysis of the parameters required by the context (temperature between 22°C and 25°C, and relative humidity between 40% and 60%) to reach thermal comfort, which have little relation to the inhabitability of naturally ventilated spaces during the entire year.

METHODOLOGY

The urban-architectural proposal in question, emerges from a fourth year projects workshop in the Architecture Program, which uses the Solar

Parameter	Values set
Indoor room temperature (Ta)	22°C a 25°C
Relative humidity (%)	40% a 60%

Table 1. Thermal parameters proposed by the Solar Decathlon LAC 2019 Contest. Source: Solar Decathlon (2019).

Decathlon LAC 2019 international contest as the reference framework, which places emphasis on using renewable energy, comfort, and protecting the environment. The project made for the contest is called TUHOUSE, and for its two and a half year development, a multidisciplinary team of students (50) and professors (10) was formed, from two universities in the region (San Buenaventura-Cali and Autonoma de Occidente), with complementary knowledge in the areas of bioclimatic architecture, habitat, urban agriculture, environment, sustainability, and renewable energies. This allowed not just addressing all the issues requested by the contest, but addressing them in an innovative way, through an interdisciplinary approach (Baumber, Kligyte, Bijl-Brouwer, Van Der & Pratt, 2020; Herrera, Rey, Hernández & Roa, 2020).

The main stages of the work were: a) urban and architectural grounds, considering the place and the population; b) thermal-energy simulation; c) costs; d) prefabrication and construction of a housing prototype at a 1:1 scale; and, e) monitoring and verification of the operation of the strategies.

Methodologically speaking, for the design phase, the proposal was developed in an applied research laboratory-workshop, which involves project, sustainable and bioclimatic aspects, alternating the design processes with checks, using software simulations (like Formit and DesignBuilder) and observations in the bioclimatic laboratory (heliodon and smoke table). Once the prototype was built in a later phase, a series of measurements were made onsite. This methodology, inherent to the bioclimatic process (San Juan et al., 2013), which incorporates bioclimatic analysis, initial and final sizing, and measurements to compare hypotheses, is very rewarding in the students' learning process, as it passes from the conventional design to the energy optimized one (Montoya, 2020), and transcends learning in the classroom, to originate the possibility of facing the knowledge received from real actions as well as from confirming the results.

After the prototype was made at the site determined by the contest, called Villa Solar, continuous indoor measurements were made of the room temperature (°C), relative humidity (%), air quality (CO_2), illuminance (lux) and energy generation with the specialized equipment provided by the contest. In addition, specific measurements were made on the elements of the envelope, both inside and outside, with a Nubee infrared thermometer. The energy consumption (kWh) was measured through specific tasks on the prototype, that implied using household appliances and devices. The acoustic parameters, like the sound pressure level (dB) and the reverberation time, were measured on a specific day by the organizers using specialized equipment. In terms of thermal comfort, the values indicated in Table 1 would need to be reached.

To analyze the thermal comfort, the range proposed by the contest was compared with the range proposed by the adaptive model (ASHRAE/ANSI, 2017), indicated in Equation 1:

$$Tacep = 0.31*T(pma\ (out)) \pm 17.8 \pm T\_lim \quad (1)$$

Where:
Tacep =Acceptable temperature
T(pma(out) = Average outdoor temperature
T_lim = Temperature Limits, which can be ±3.5 for an acceptance of 90%. (Nicol *et al.*, 2012).

RESULTS AND DISCUSSION

THE URBAN PROPOSAL

The urban proposal is based on a sustainable design of a high-rise social housing complex, of 5 and 8 floors, and a density of 120 dwellings/hectare. The complex is formed using an urban grouping system of buildings that form public and private urban spaces, capable of adapting to the different social and climate contexts of each place. In some cases, the common space par excellence is the site, and in others, the street. Both foster meeting, identity and co-existence. In the words of Samper: "What is key is not the design of the dwellings themselves, but rather the search for new urban patterns. Working to seek new urban patterns implicitly leads to new dwelling typologies[1]" (2003, p. 20)

1 Free translation

Surface	Exposed to the sun	In the shade
Concrete	49.2°C	28.3°C
Outdoor paving stones	39.4°C	29.1°C
Earth with vegetation	35.4°C	27.0°C

Table 2. Reduction in temperatures, TUHOUSE project. Source: Prepared by the Authors.

The careful layout of the buildings (orientation, distancing and height) manages to form shaded spaces which, accompanied by native trees and vegetation, allow a significant reduction of solar irradiance, generating a suitable micro-climate. Wind plays a key role when it comes to dissipating the heat produced by the materials and elements of the project. The succession of broad (premises) and narrow spaces (streets and entrances), produce the so-called "Venturi effect" which, along with the presence of green facades in narrow places, achieves a passive cooling of the winds that enter the complexes. These are all strategies for the warm climate of Cali recommended by emblematic authors (Olgyay, 1963) (Figure 1). According to the measurements taken in situ, these strategies manage to reduce temperatures by up to 10 degrees (Table 2).

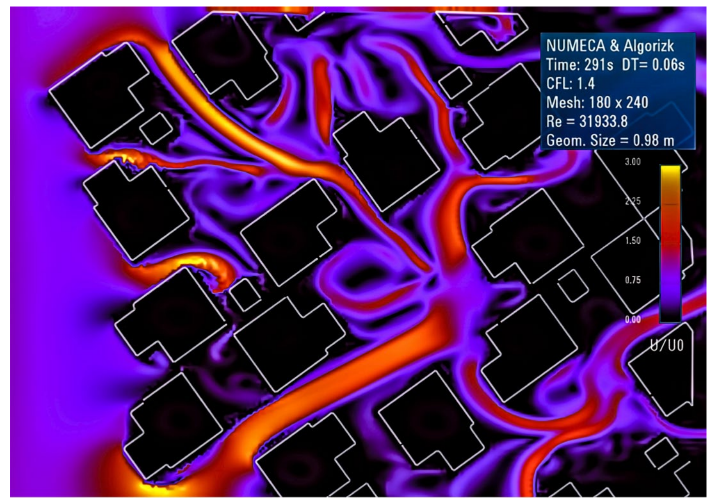

Figure 1. Wind behavior. Wind Tunnel. Source: Prepared by the Authors.

The housing complex also has cultural, educational and productive facilities; a bicycle mobility system connected to the city's cycle-path network; and a productive urban orchard and fruit tree system, that generates additional income for the complex's inhabitants while fostering environmental quality. In the understanding that the quality of life is not exclusively limited to inhabitability inside the dwelling, the idea is to minimize possible negative impacts and promote the sustainable use of common spaces (Cobo *et al.*, 2019) (Figure 2).

Figure 2. Image of the complex's public space. Source: Prepared by the Authors

ARCHITECTURAL AND SUSTAINABLE PROPOSAL

This proposal considers that social housing must comply with 4 basic conditions to be inhabitable and sustainable: the housing must be progressive and productive (Samper, 2002), as well as replicable and flexible, the main principles that allow different families to freely live. The housing spaces must allow adapting to the changing needs of the family, just as the AURA team (University of Seville, Spain and Santiago de Cali University, Colombia) proposes, implementing progressive modular systems and flexible spaces determined by the real estate (Herrera, Pineda, Roa, Cordero & López, 2017). Something that does not occur with the current offer, where families have to adapt to the dwelling. In order to attain this quality, the dwellings must be laid out from the start, to be open to extensions and remodeling as the family deems fit, and so that, they can even become a source of income, namely productive dwellings. These are principles that were tried out in the last version of the Solar Decathlon contest, in 2015, and that demonstrated their urban and architectural feasibility as a system (Cobo *et al.*, 2019).

The project process must also be sustainable: optimizing design processes to then optimize construction processes and the use of resources. It is for this reason that the proposed housing unit is

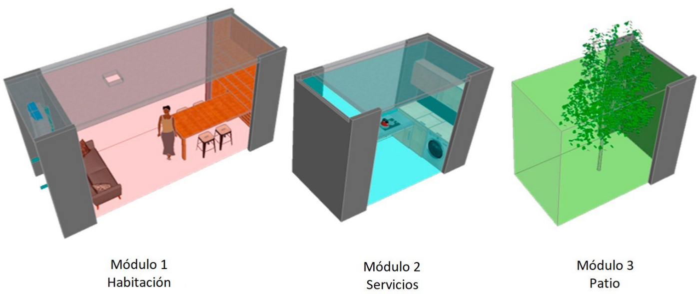

Figure 3. Prototype modules. Source: Prepared by the Authors.

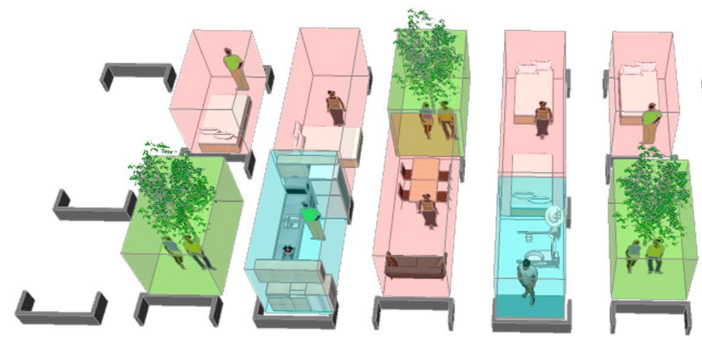

Figure 4. Flexibility and progressiveness. Source: Prepared by the Authors.

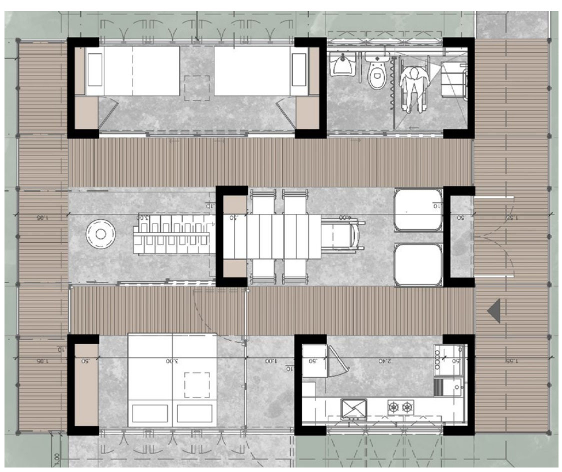

Figure 5. Floor Plan. Source: Prepared by the Authors.

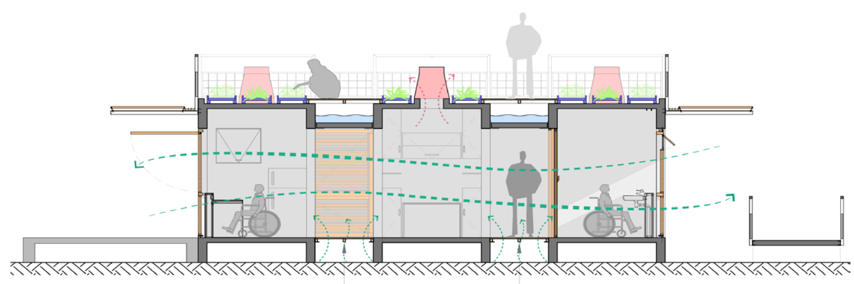

Figure 6. Cross-section. Source: Prepared by the Authors.

conceived as a "Lego", formed by two base modules, where the space-shape-structure is defined in a single element (Figure 3).

The rooms -bedroom, dining room, living room, study- are laid out in the larger module, and the services -kitchen, bathroom, yard-, in the smaller module. The way in which these units are organized, considering a circulation system and around a yard, allows forming a variety of flexible and progressive housing units, both in use and in construction, to house different types of families (Figure 4). This layout also allows taking advantage of the environmental conditions that the yards of traditional houses in the region provide, like shading, ventilation, moisture and cooling by evaporation (Figure 5), in a similar way to other prototypes of Solar, like Patio 2.12, which revisits the traditional Andalusian house, and incorporates passive strategies that respond, among other factors, to the hot summer, in a similar way to the case presented here (Terrados, Baco & Moreno, 2015).

Alongside providing shelter, the outlined dwelling generates food (on its roof and facades), comfort and energy. The proposal reuses graywater and collects rainwater; uses technology and materials that are environmentally sustainable; is coherent and effective in different settings and facing the problems of urban density (Figure 6).

In addition, this is a self-sustainable and efficient project, where each element it has, has several roles. The east-west façade and the roof (the ones affected most by solar radiation), are covered by a green envelope that has three main roles: insulating the concrete structure from solar radiation -which constitutes one of the main recommendations for a tropical climate (Evans & Schiller, 1994; Konya, 1980)-, producing food and purifying the air, contributing to reduce environmental contamination. The design includes a bioclimatic transition space between the indoors and outdoors (Figures 7 and 8, and Table 3), similar to the hallway of traditional houses in the region (Herrera *et al.*, 2017).

The south-north facades are open to take advantage of the cross circulation of the wind -another strategy suggested for a tropical climate (Olgyay, 1963)-,

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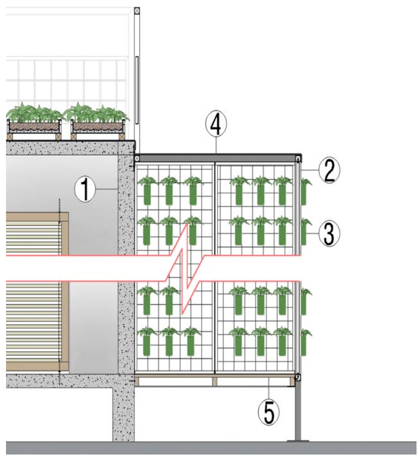

Figure 7. Facade cross-section. Source: Prepared by the authors

Figure 8. Entrance space, green envelope. Source: Prepared by the authors.

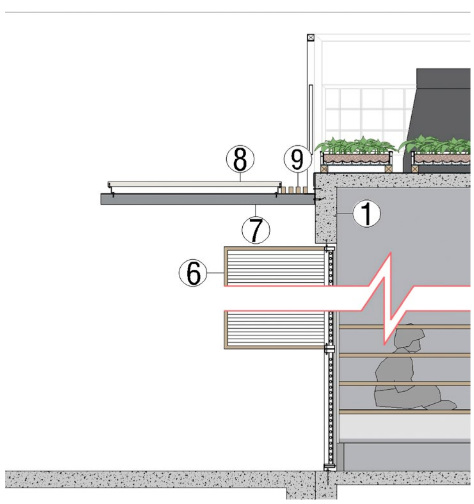

Figure 9. Cross section along the facade. Source: Prepared by the authors.

Figure 10. South facade. Source: Prepared by the Authors.

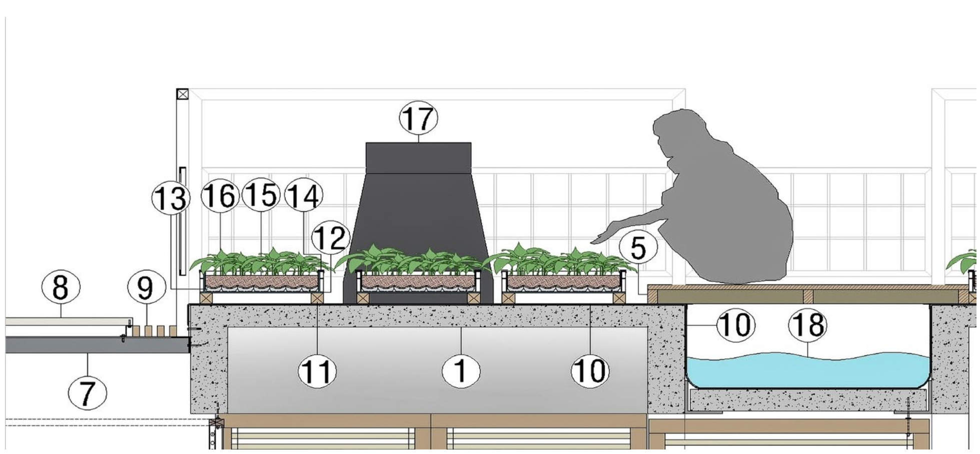

Figure 11. Detail of the proposing dwelling roof. Source: Prepared by the Authors.

Location	No.	Materials	Thickness	Conductivity
Wall	1	3000 Psi reinforced concrete	10	0.97
Facade cage	2	Electro-welded metal mesh	5	58
		Bamboo	60	0.28
Green facade	3	Recycled PET plastic bottles	2	0.24**
		Earth	60	0.8*
		Aromatic plants	-	-
Cage roof	4	35% black polyshading (LXA) Anti-UV (Polyethylene)	1	0.35
Pallet floor	5	Wood	25.5	0.15
Facade windows	6	Wooden strips	25.5	0.15
		Bamboo poles	60	0.28
Eave	7	Solar panel metal support structure	38.1	0.28
	8	Solar panel	70	1.05
	9	Monterrey pine wooden beams	50.8	0.28
Roof	10	TPO SINTOFOIL SIL waterproof membrane (EELAB certified) (ethylene-propylene)	1.2	0.24
	11	Monterrey pine wooden steps	50.8	0.28
	12	Recycled plastic baskets	25.4	0.50
	13	Base of personal PET bottles	2	0.24
	14	NT 1600S Geotextile (polypropylene)	1.5	0.24
	15	Wet earth	150	0.8*
	16	Plants	-	-
	17	Aluminum sheet solar chimney	5	204
	18	Concrete water channel	10	0.97

Table 3. Thermal conductivity of the materials used in building the TUHOUSE prototype.Source: IRAM 11601 (2002); Van der Vegt & Govaert (2005).

and are protected by large eaves which, apart from producing shading and protecting from the rain, support the solar panels that provide solar energy to the dwelling (Figures 9 and 10, and Table 3).

Special attention must be paid to the fifth façade, especially in the context of Cali, due to its warm climate conditions, but also because of the social conditions (Sánchez, 2019). A covered orchard was designed here, which is used to collect rainwater in the two large channels placed under the removable wooden pallets, and that work for circulation (Figure 11). This technique also allows airing the roof through a ventilated chamber (Table 3), as a bioclimatic strategy focused on the horizontal surface, which receives at least 50% of the solar radiance in the tropics (Olgyay, 1963).

Using these criteria, the hypothesis held by Becker, Goldberger and Paciuk (2007) is reinforced, who suggested that the design aspects with the highest impact on climate control, are the orientation, the openings on facades, and the thermal resistance of the walls and roof.

ENERGY AND ENVIRONMENTAL PARAMETER MEASUREMENTS

The outdoor environment temperature (Ta) measurements have average values of 24.5°C, with maximums of 32.4°C and minimums of 18.2°C. While the average outdoor relative humidity is 74.5%, with a maximum of 94% and minimum of 45%. These values are consistent with the local weather conditions, which have minimum variations during the year, typical of

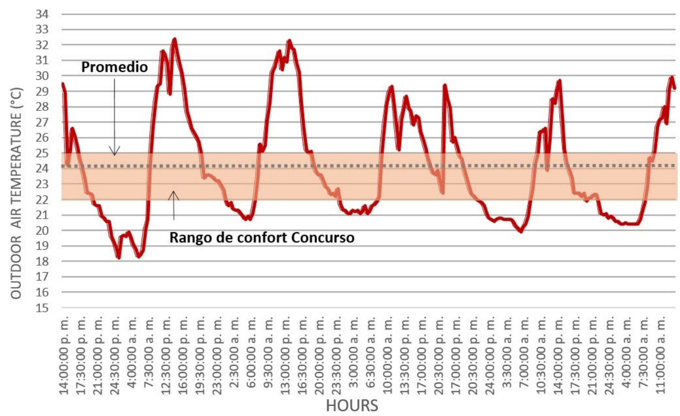

Figure 12. Outdoor temperature. Source: Prepared by the authors.

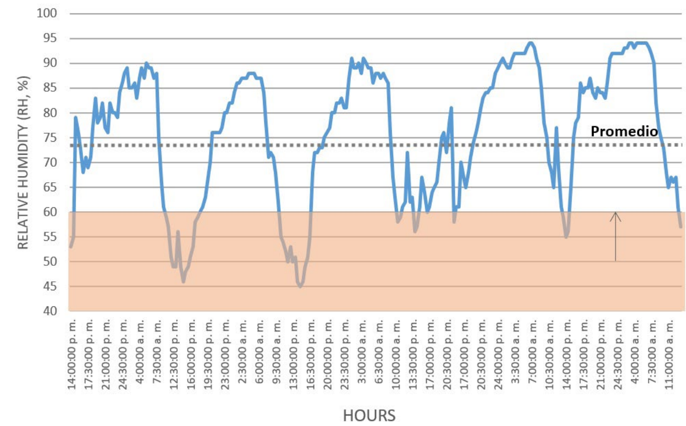

Figure 13. Outdoor relative humidity. Source: Prepared by the authors.

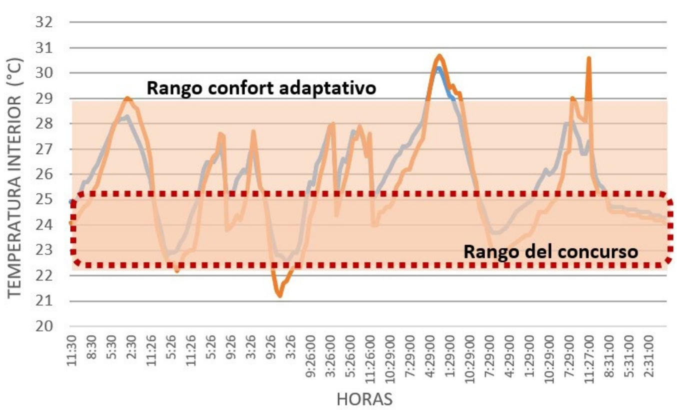

Figure 14. Temperature inside the prototype. Source: Prepared by the authors.

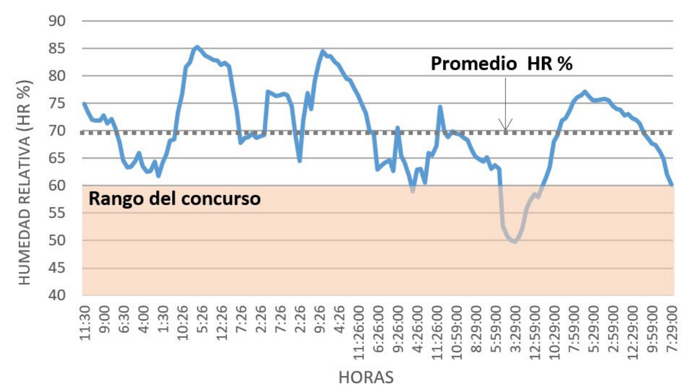

Figure 15. Relative humidity inside the prototype. Source: Prepared by the authors.

tropical and equatorial contexts, like that of this study.

Figures 12 and 13 present the records taken during the 7 days of competition. In these graphs, the hygro-thermal comfort values indicated by the contest can also be seen, along with those of the local conditions, typical of tropical regions.

Regarding the behavior of the spaces inside the prototype, in Figure 14 it can be seen that, despite maintaining an average indoor temperature of 25°C, it is only the during the morning and the early hours that the comfort range proposed by the contest is reached. On the other hand, if the comfort analysis is made using the comfort range proposed by the adaptive model, it is between 21.8°C and 28.8°C (see Equation 1), typical of the tropical contexts and of buildings with natural ventilation, and we see that most days and temperatures are outside the range.

Regarding relative humidity, the values were outside the range of the contest and close to those recorded outdoors, which correspond to naturally ventilated buildings. As can be seen in Figure 15, the average of 70% RH inside the prototype, was close to the outdoor average recorded during the same days (75% RH).

By focusing the analysis of measurements during a typical day of the competition, it is possible to see (Figure 16) that, according to the range proposed by the contest, the prototype is in comfort only at night and early in the morning. While, under the adaptive model, it is only outside the comfort range during the afternoon (1:30 to 4:30pm), with temperatures close to 29°C. This has important energy implications, given that facing a higher comfort requirement, as is the case of analysis considering the range indicated by the contest, using the international standard (designed for other contexts with marked seasons), a thermal design can be assumed that implies a higher energy consumption derived from the need to cool the dwelling's internal conditions.

Photovoltaic panels are implemented that capture solar energy to convert it into electricity, generating

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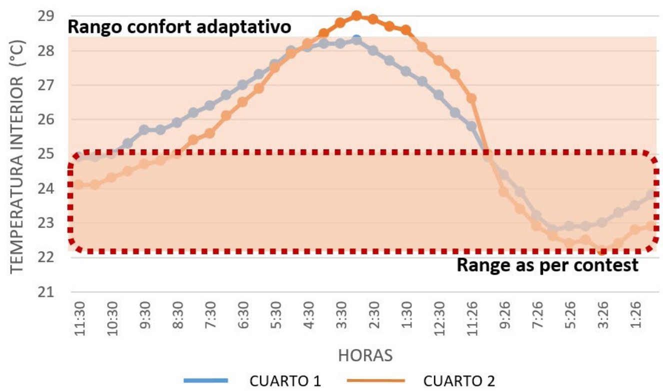

Figure 16. Temperature of a typical day inside the TUHOUSE prototype. Source: Prepared by the authors.

energy self-sufficient homes, to reduce carbon dioxide emissions through the photovoltaic system that produces 3578 kWh a year. By using electricity efficiency, the project's consumption is reduced by almost 40%, which is equal to 1166 kWh saved a year.

The average daily energy consumption of the prototype remained the same during the 8 days of the competition at 58 kWh, responding to the goal of the contest to keep it under 70 kWh. This was achieved thanks to high efficiency household appliances and LED lightbulbs for lighting. Regarding the energy balance, ideal at 0 kWh, was -3.4 kWh here, as a difference between the energy exported to the grid (35.98 kWh) and that imported (39.39 kWh), which allowed it to come third in this test (Macias, 2020).

In sustainability terms, the reuse of graywater (after treatment) is laid out, alongside taking advantage of rainwater for activities that do not require drinking water and that represent an elevated percentage in the home's daily consumption, such as the use of toilets and the green areas and garden watering. The shower and handbasin graywater are collected, in a so-called "eco-guardian" device, to reuse it in cleaning tasks. A rainwater storage tank and interceptor system are also implemented. All this with the purpose of reducing drinking water consumption by 16%, and the amount poured into sewers by 40%. These strategies seek to offset the costs of the drinking water and sewerage service.

The project reduces waste generation for final disposal, correctly separating waste at the source, and disposing organic waste in a composting unit. Using these two measures, around 80% of that generated is used. Alongside this, strategies are proposed to suitably manage the solid waste generated in each one of the phases: construction, operation and demolition.

As a contribution to sustainability, the housing prototype is built with a system of large prefabricated concrete pieces, made from different components that are considered industrial waste, like furnace ash or those from burning bamboo husks from the industry of the region, supplies that also allow improving resistance in the mixes used. This concrete, once its service life is over, does not just become a recycling material for manufacturing non-structural elements, like floor stones, eventually whole pieces can be reused in another type of construction, achieving from this point of view, a high sustainability.

CONCLUSION

The bioclimatic design process implemented in the transversal and interinstitutional course, allowed testing the design decisions made through measurements and simulations, to finally apply the knowledge acquired, in the construction of the prototype in Villa Solar. This was possible thanks to contests like Solar Decathlon, which encourages a dynamic of theoretical-practical learning, essential for Architecture Faculties.

In this framework, the successful behavior of architectural strategies was verified while providing comfort: shading on concrete surfaces exposed to radiation, forming a thermal mass, especially on the roof through the orchard, green envelope, crossed ventilation, permeable façade for ventilation and constant air renewal. Strategies which, with a doubt, were explored for other prototypes of the contest through interesting variations and applications.

The good thermal performance of concrete was shown through the prototype, relevant evidence if it is considered that this is the main material social housing is currently built with, using strategies like shading and double facades, to achieve a comfort situation in terms of the adaptive comfort model.

As has been shown, the ranges demanded by the contest do not match the tropical climate of Cali. This leads to needing to revise said ranges for future versions of the competition in tropical settings. The ranges proposed promote a higher thermal demand and, therefore, the presence of prototypes with mechanical climate control to reach said values, which is uncommon in social housing in Latin American cities.

Finally, it is worth mentioning that, for the competition and execution times, the prototype could not be built in RCA. However, this is a challenge for the future. On the other hand, it is important to highlight that the measures focused on using single-use plastic waste were successful, as a result supplies were generated for elements of the envelope, the seeding and other architectural components, which will be explored further once the prototype is converted in the Housing Laboratory, led by the two universities involved in this project.

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OFFICE USER WORK PERFORMANCE INDICATOR IN WARM TEMPERATE SUMMER PERIOD

INDICADOR DE RENDIMIENTO LABORAL DEL USUARIO-TRABAJADOR DE OFICINA EN PERÍODO DE VERANO DE CLIMA TEMPLADO CÁLIDO

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RESUMEN

El objetivo del trabajo que aquí se presenta fue desarrollar una herramienta metodológica que evaluara el rendimiento laboral de los espacios de oficina durante el período de verano. La herramienta propuesta se tradujo en un indicador de rendimiento laboral óptimo denominado IRLO, que combina variables ambientales de influencia térmica, calidad del aire, visual y acústica. Para su desarrollo, se practicaron mediciones integradas y, paralelamente, encuestas a los usuarios-trabajadores de un edificio de oficinas de la Ciudad de San Juan-Argentina. Los resultados develan los rangos de preferencia de cada variable, reconociendo que en las oficinas de tipología abierta acontece una mayor capacidad adaptativa ambiental que en las de tipología cerrada. Se concluye que el indicador destaca por sentar una base para identificar rendimientos laborales conforme a variables ambientales que deben, en adelante, ser consideradas en fase de diseño.

Palabras clave
calidad ambiental, edificio de oficinas, tipología

ABSTRACT

The purpose of this work was to develop a methodological tool to evaluate office space work performance during the summer period. The proposed tool is an optimal work performance indicator called IRLO, which combines environmental variables on thermal, air quality, visual and acoustic influence. Integrated measurements were run for its development alongside surveys to users-workers of an office building in the city of San Juan - Argentina. The results reveal the preference ranges of each variable, recognizing that in open plan offices, there is a greater environmental adaptive capacity than in closed plan offices. It is concluded, that the indicator stands out by providing a basis to identify work performance considering environmental variables that should, in the future, be considered in the design phase.

Keywords
environmental quality, office building, typology

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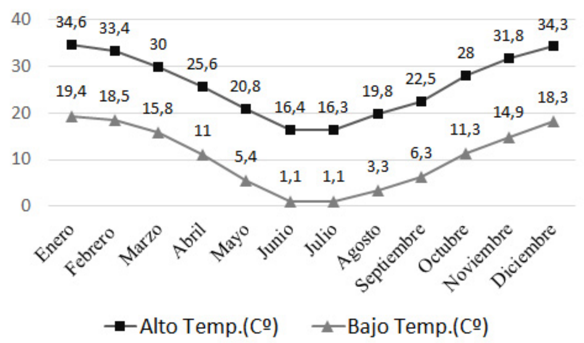

Figure 1. Mean maximum and minimum annual temperatures (Cº)-San Juan, Argentina.

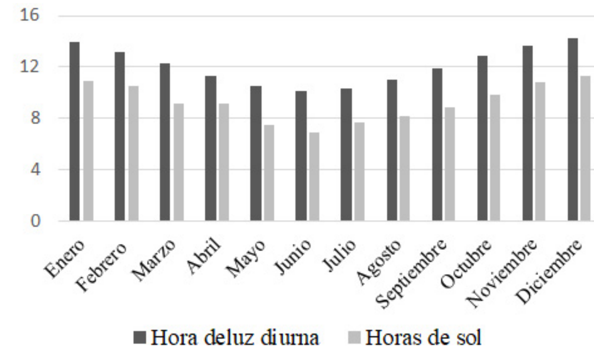

Figure 2. Daylight / Sunlight hours (annual) -San Juan, Argentina. Source: Prepared by the authors based on data from Weather Atlas.

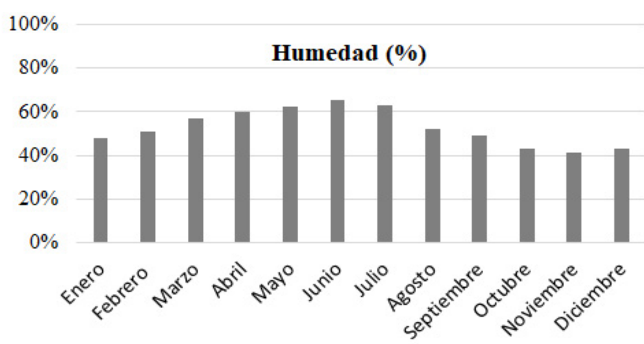

Figure 3. Annual humidity percentage (%)-San Juan, Argentina. Source: Prepared by the authors based on data from Weather Atlas.

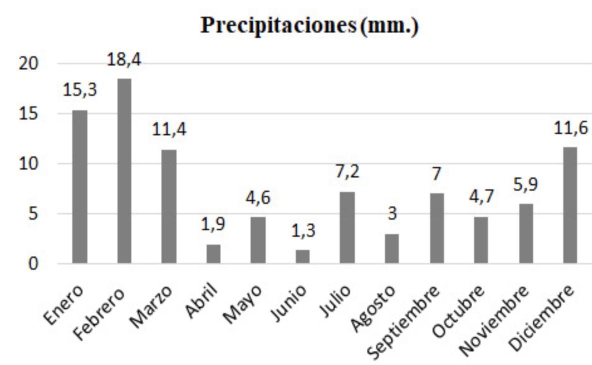

Figure 4. Mean annual rainfall (mm)-San Juan, Argentina. Source: Prepared by the authors based on data from Weather Atlas.

INTRODUCTION

In the world, a fifth of the population inhabits their work spaces more than 48 hours a week (International Labor Organization [ILO], 2020). These spaces are diverse, depending on the type of activity taking place. In Argentina, 60% of them are from the office sector (National Institute of Statistics and Censuses [INDEC], 2010). These work sites are conceived in terms of elements containing the roles that users-workers (UW) perform, underestimating the important of indoor environmental quality (IEQ) (Marín Galeano, 2013), which is a priority, given that the spatial setup modifies environmental factors, and a result, has an influence on the sensation of comfort and work performance (WP) of the UW (Nag, 2019).

From the scientific world, progress has emerged on the topic, indicating the indoor environmental variables that have the greatest impact on health and performance (WEI *et al.*, 2020) and that, at the same time allow understanding issues related to spatial design. Among these the temperature (Wargocki & Wyon, 2017; Lamb & Kwok, 2016; Maula, Hongisto, Koskela & Haapakangas, 2016), CO_2 concentration (Candanedo & Feldheim, 2016; Shriram, Ramamurthy & Ramakrishnan, 2019), lighting level (Liu, Lin, Huang & Chen, 2017, Yang & Moon, 2019; H. Wu, Y. Wu, Sun & Liu, 2020), and the indoor noise level (Liebl & Jahncke, 2017; Kari, Makkonen & Frank, 2017) stand out. There is also research that addresses these variables holistically, seeking to find relations between them, as well as to identify those that have the greatest effect on people's wellbeing (Haegerstrand & Knutsson, 2019; Lou & Ou, 2019; Shin, Jeong & Park, 2018, Wei *et al.*, 2020). However, studies that address WP in offices and how this is holistically affected by the aforementioned variables, are not known, particularly in a warm template climate. For this reason, it is necessary to broaden knowledge focused on these latitudes, especially in a critical period, like summer.

This research has the purpose of getting to know the relationship between IEQ in offices and the WP of UW, for the purposes of determining optimal WP ranges, and making their numerical valuations. For this, an Optimal Work Performance Indicator (OWPI) is designed. In this sense, it is worth underlining that, from architectural spatiality, two clearly defined typologies are recognized, open (OO) and closed (CO). These are studied independently, seeking to find possible similarities and differences.

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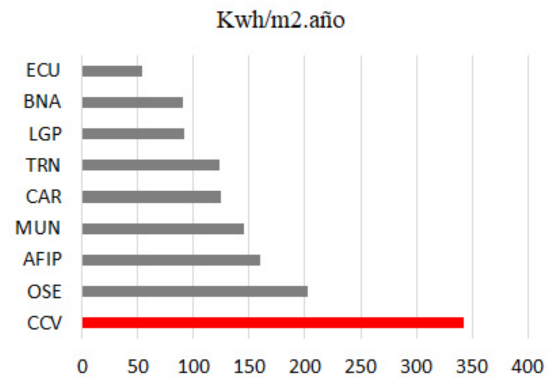

Figure 5. Electricity consumption per meter squared of office buildings located in the city of San Juan, Argentina. Source: Provincial Energy Regulating Entity.

METHODOLOGY

The research begins with an experimental approach, using field work in offices in a warm template region. Integrated measurements are made on environmental variables, enquiring about the self-reported WP evaluation, through surveys made for this research.

The ranges of highest and lowest influence on WP are obtained from the results, for each environmental variable analyzed, where these are quantitatively evaluated and graphically expressed. Finally, each one of the performance variability ranges leads to the construction of the OWPI, the target of this study.

CHARACTERIZATION OF THE SITE

The city of San Juan (Argentina) is located 630 meters above sea level, at 31.6° south and 68.5 west. The climate, according to the IRAM 1163 standard (1996), is warm template with large temperature variations (Figure 1), atmospheric transparence (Figure 2), and low humidity (Figure 3). The rainfall is continental, with a medium low frequency (Figure 4). According to the Köppen classification (Minetti, Carletto & Sierra, 1986), it is cold desert type (BWh), where winters are very cold, and summers template or warm. It has a regular moderate southeasterly wind, a characteristic dry-warm zonda wind, considered as a severe westerly event because of its intense gusts (Puliafito, Allende, Mulena, Cremades & Lakkis, 2015). It is most common in August and September (Perucca & Martos, 2012).

OBJECT OF STUDY

The choice of the case study is based on the environmental impact analysis arising from its level of consumption in the city of San Juan. For this reason, the energy consumption of buildings is analyzed and their relationship per meter squared of useful surface (with climate control), destined for work spaces (offices), considering those that exceed 3 (three) floors.

The Civic Center building (CCV) (Figures 6 and 7) has the highest electricity consumption, with values of over 340 kWh/m^2.year, which is why it was chosen as the case study. Table 1 summarizes its most relevant characteristics.

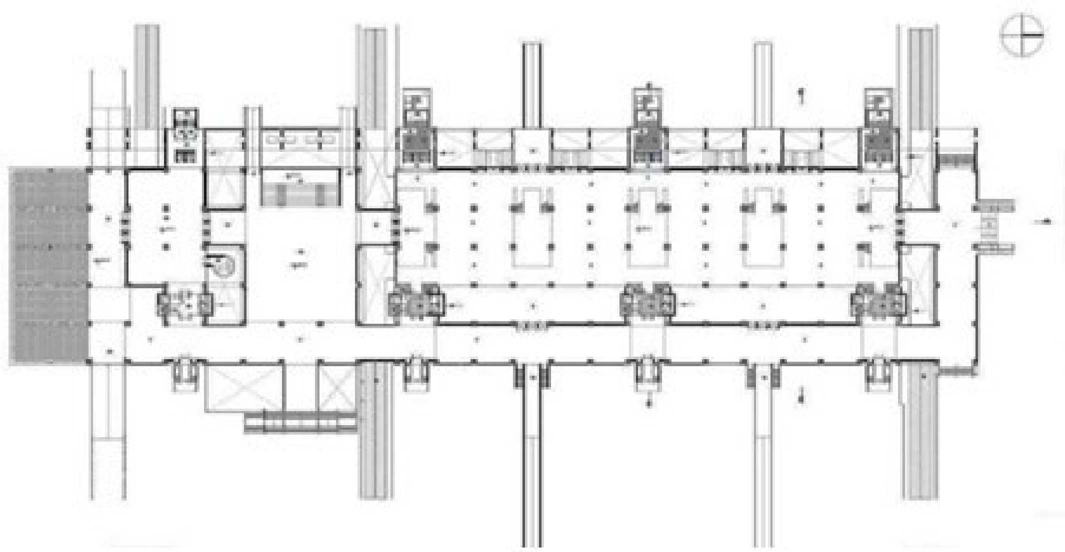

Figure 6. Civic Center Building-Ground Floor. Source: Urban Development and Planning Direction.

Figure 7. East facade Civic Center Building. Source: Preparation by the Authors. Source: Preparation by the Authors.

Total surface area	80,873m²
Orientation	East-West
Office Surface area [%]	59%
Hold-Cold climate control system	HVAC (Heating-Ventilation-Air-Conditioning)
Consumption [kWh/m2.year]	342
Structure type	Reinforced Concrete
Enclosure masonry	Light mdf sheet
Glazed surface for open office	0%
Glazed surface for closed office	50%
Lighting system	Circuits differentiated by floor (led system)
Number of UW	4046
UW surveyed	636

Table 1. Characterization of the Civic Center building Source: Preparation by the Authors.

Characterization	Closed office (CO)	Open Office (OO)
Presence of windows	Yes	No
Possibility to open	Yes	No
Daylight control	Yes	No
Height of enclosure-panel	3.60 m. (100%)	0.80 m - 2.10 m. (25 %)
Average occupation factor	5.10 m^2/people	4.50 m^2/people
Capacity	2 to 6 people	3 to 11 people
Activity	Internal Work	Internal work-attention to the public

Table 2. Typological characterization of Offices. Source: Preparation by the Authors.

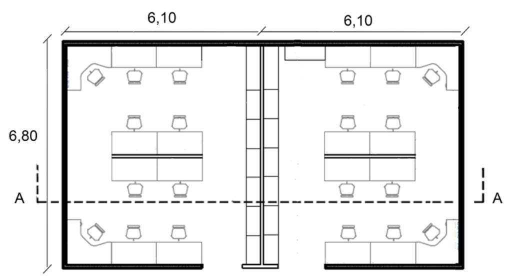

Figure 8. Standard floor plan of two open architectural typology offices (OO). Measured in meters. Source: Preparation by the Authors

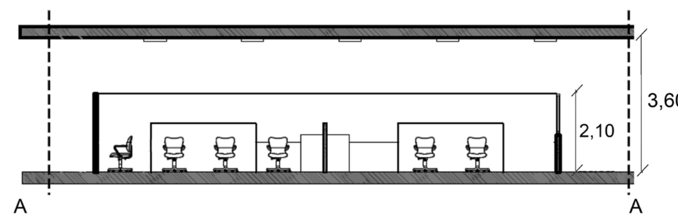

Figure 9. Cross-section of the two open architectural typology offices (OO). Measured in meters. Source: Preparation by the Authors.

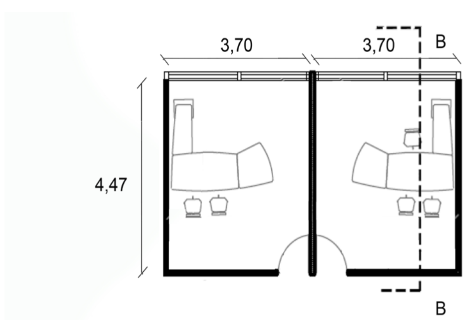

Figure 10. Standard floor plan of two closed architectural typology offices (CO). Measured in meter. Source: Preparation by the Authors.

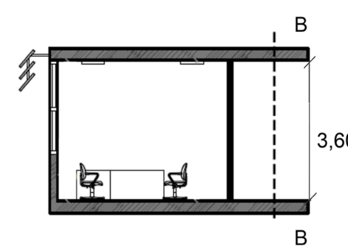

Figure 11. Cross-section of the two closed architectural typology offices (CO). Measured in meters. Source: Preparation by the Authors.

CLASSIFICATION OF OFFICE SPACES

The variability of IEQ requires distinguishing elements and grouping them by their characteristics. It is for this reason that in this work, office spaces are distinguished as OO (Figures 8 and 9) and CO (Figures 10 and 11). Both have differences that stand out, which a priori leads to thinking about the advantages of the CO over the OO (Pan *et al.*, 2018). Table 2 shows the characteristics that allow establishing the main comparisons.

MEASUREMENT SYSTEMATIC

To collect data, the "Spot" type systematic (focused) was used, based on the techniques of De Dear (2004) and Kuchen and Fisch (2009), and adapted to the collection of the four environmental variables. In this framework, a mobile measurement unit (MMU) is designed (Figure 12), which allows examining 164 spaces, with 636 surveys made during the summer period.

Figure 12. Mobile measurement unit. Source: Preparation by the Authors.

The MMU comprises sensors (Figure 13) that are capable of identifying the following factors:

a. Thermal comfort: HOMO U12-006 sensor. This allows measuring the air temperature (°C) in a range of +40 to + 100°C, with a precision of ±0.5°C to 20°C, in humidity conditions of 5 to 95% H.r without condensing. A stabilization time of between 4 to 5 minutes (in static air) is needed for the measurement.
b. Thermal comfort: Ajavision WH380 laser infrared thermometer. This allows measuring the mean radiant temperature (°C) in a range of +50°C to +380°C. It has a precision of ±3°C.
c. Air quality: TELAIRE 7001 sensor. This allows measuring CO_2(ppm) levels in a range of 0 to 2500 in real time. It has a reading sensitivity of ±1ppm and accuracy of ±50ppm.

Figure 13. Comfort/performance sensors. Source: Preparation by the users.

CONICET

IRPHa

Género ○ F ○ M	Edad: ____________	¿Se fuma en su oficina? ○ si ○ no	Horas al día que trabaja______

Preguntas acerca del ambiente interior de su oficina

1. ¿Cómo percibe la temperatura en este momento? *(En una escala de 7 puntos marcar la opción correspondiente)*						
○	○	○	○	○	○	○
mucho frío	*frío*	*algo de frío*	*confortable*	*algo de calor*	*calor*	*mucho calor*

2. ¿Siente que su rendimiento se ve afectado negativamente por la temperatura interior en este momento?	*si*	○	*no*	○

3. De ser así: ¿En qué grado afecta negativamente a su rendimiento la temperatura en este momento?				
○	○	○	○	○
Nada (0%)	*Bajo (25%)*	*Medio (50%)*	*Alto (75%)*	*Muy alto (100%)*

4. ¿Cómo percibe la calidad del aire en este momento? *(En una escala de 7 puntos marcar la opción correspondiente)*						
○	○	○	○	○	○	○
muy mala	*mala*	*algo mala*	*regular*	*algo buena*	*buena*	*muy buena*

5. ¿Siente que su rendimiento se ve afectado negativamente por la calidad del aire en este momento?	*si*	○	*no*	○

6. De ser así: ¿En qué grado afecta negativamente a su rendimiento la calidad del aire en este momento?				
	○	○	○	○
Nada (0%)	*Bajo (25%)*	*Medio (50%)*	*Alto (75%)*	*Muy alto (100%)*

7. ¿Cómo percibe el nivel de ruido en este momento?						
○	○	○	○	○	○	○
Nada ruidoso	*Casi nada ruido.*	*Poco ruidoso*	*Medio*	*Algo ruidoso*	*Ruidoso*	*Muy ruidoso*

8. ¿Siente que su rendimiento se ve afectado negativamente por el nivel de ruido en su oficina en este momento?	*si*	○	*no*	○

9. De ser así: ¿En qué grado afecta negativamente a su rendimiento el nivel de ruido en este momento?				
Nada (0%)	*Bajo (25%)*	*Medio (50%)*	*Alto (75%)*	*Muy alto (100%)*

10. ¿Cómo percibe la iluminación en este momento? *(En una escala de 7 puntos marcar la opción correspondiente)*						
○	○	○	○	○	○	○
Encandila	*Demasiado luminoso*	*Luminoso*	*Algo luminoso*	*poco luminoso*	*Algo oscuro*	*Muy oscuro*

11. ¿Siente que su rendimiento se ve afectado negativamente por el nivel de iluminación en este momento?	*si*	○	*no*	○

12. De ser así: ¿En qué grado lo afecta negativamente el nivel de iluminación de su oficina en este momento?				
○	○	○	○	○
Nada (0%)	*Bajo (25%)*	*Medio (50%)*	*Alto (75%)*	*Muy alto (100%)*

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CONICET

Figure 14. Survey made to UW. Source: Preparation by the Authors.

d. Visual comfort: YK-2005LX light meter sensor. This allows measuring illuminance levels (lux) on the work plane, in a range of 000/100, 000Lux in real time, with a spectral sensitivity that follows the requirements of the CIE (International Commission on Illumination) curve with an accuracy of ± 4%+2 digits).
e. Acoustic comfort: SL-4023SD decibel-meter sensor. This allows measuring noise levels (dB) in an automatic range of 30 to 130 dB and in a manual range (3 ranges) of 30 to 80 dB, 50 to 100 dB and 80 to 130 dB. Time weight: quick/slow. Frequency weight of A (dBA) / C(dBC). The measurement made in this work was done in a range of 50 to 100 dB, with a slow time weight and A frequency weight.

The measurement begins by positioning the MMU alongside a work space (desk) used by a sat UW, at a distance of 0.50 meters from one another, and at a height of 0.90 m above the floor level.

Survey

The survey helps to make a diagnostic of UW, that summarizes the effect of the influence variables. Among the questions asked, those that inquire about the Performance Vote (PV) of the UW become relevant. These are based on studies made by Humphreys and Nicol (2007), where they ask to what extent (0-100%) do they feel that IEQ negatively affected their WP. Figure 14 shows the survey questions made about the perception of IEQ by the UW, which allows obtaining the subjective data.

IMPLEMENTATION AND RESULTS

WP ranges are built as a means to get to know the degrees of "vulnerability" of the UW, depending on the influence variable by office typology. The steps for its construction are detailed in this section.

1. The PV values of each environmental variable in which the UW self-reports zero influence (0%) on their performance, are recorded.
2. The maximum and minimum Thermal/Performance Vote (PVt), Air Quality/Performance Vote (PVa), Illuminance Level/Performance Vote (PVi) and Noise/Performance Vote (PVn) are defined, which determine the maximum possible variability of each environmental influence parameter.
3. The intermediate ranges are defined considering the division between the optimal value (PV=0%) and the maximum value, and the division between the optimal value (PV=0%) and the minimum value.
4. Finally, to obtain the ranges, numerical equivalents are defined (EqN) and scoring intervals to establish the qualitative evaluation of each range, from "excellent" with an EqN equal to 5, to "bad", with an EqN equal to 1, for PVt, PVa, PVi and PVn, as indicated in Table 3.

Qualitative evaluation	Numerical evaluation (EqN)	Scoring Interval
Excellent	5	4.2< to ≤ 5
Very Good	4	3.4 < to ≤ 4.2
Good	3	2.6 < to ≤ 3.4
Regular	2	1.8 < to ≤ 2.6
Bad	1	1 ≤ to ≤ 1.8

Table 3. Numerical equivalents of the performance ranges. Source: Preparation by the Authors.

ANALYSIS OF THE RESULTS

The relationship between each range by study variable and the WP variability valued qualitatively and quantitatively by means of EqN is shown in Tables 4 to 7, making a distinction between office typologies. In addition, each table is summarized in graphs comprising an X-axis for the measurement values of each environmental variable, and a Y-axis, for the EqN of the analysis variables.

The highest or lowest amplitude of the ranges in the graphs is associated to the UW's capacity to adapt regarding the variable in question. It is seen that these are represented with one or two poles of disconformity, depending on the environmental variable analyzed. Each one of these is described below.

Operating temperature

The operating temperature values are taken to evaluate the WP affected by thermal variability, since this represents the temperature perceived by a person in an indoor environment. This constitutes the average between the air temperature and the mean radiant temperature, measured in degrees Celsius (°C).

Table 4 shows the WP variability considering the operating temperature ranges by office typology, while Figures 15 and 16 graphically represent the results obtained.

From the analysis made, it can be highlighted that the WP ranges found in the OO typology, have a greater amplitude compared to CO. This is seen to a greater extent on analyzing the "excellent" range. The variability for this level is of 0.8°C in OO, while in CO it is 0.3°C. This situation allows confirming that the UW of OO have a greater capacity to thermal adaptation compared to the CO. After this, it is noticed that there is a preference to work with higher temperatures in UW of CO, this is distinguished more on comparing the "excellent" range of both typologies, with the variability for OO being between 24.7 and 23.9°C, while for the CO, this variability increases on being 25.1 to 24.9°C.

Open Office (OO)									
Qualitative evaluation	Bad	Regular	Good	Very Good	Excellent	Very Good	Good	Regular	Bad
EqN	1	2	3	4	5	4	3	2	1
Maximum [C°]	<21.5	≤22.3	<23.1	<23.9	<24.7	<25.5	<26.3	<27.1	-
Minimum [C°]	-	21.5	22.3	23.1	23.9	24.7	25.5	26.3	≥27.1
Closed Office (CO)									
Qualitative evaluation	Bad	Regular	Good	Very Good	Excellent	Very Good	Good	Regular	Bad
EqN	1	2	3	4	5	4	3	2	1
Maximum [C°]	<22.8	<23.5	<24.2	<24.9	<25.1	<25.8	<26.5	<27.2	-
Minimum [C°]	-	22.8	23.5	24.2	24.9	25.1	25.8	26.5	≥27.2

Table 4. Valuation of WP ranges (of thermal impact) during the summer period for OO and CO. Source: Preparation by the Authors.

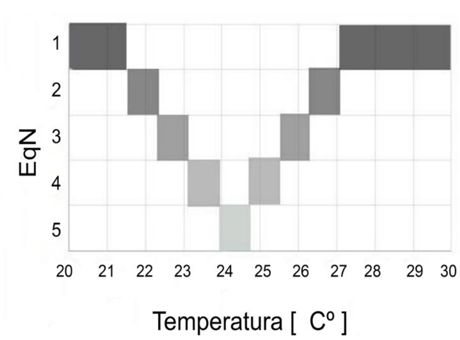

Figure 15. Variability ranges of WP affected by operating temperature during the summer in OO. Source: Preparation by the Authors.

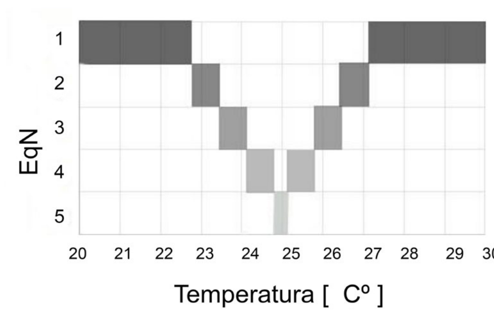

Figure 16. Variability ranges of WP affected by operating temperature during the summer in CO. Source: Preparation by the Authors.

Air Quality

The air quality is measured in the carbon dioxide (CO_2) concentration levels present. Said levels, dependent on the presence of people and the renewed air percentage, could affect the comfort of the UW, and with this, their WP. The CO_2 levels are measured in ppm (parts per million) in each analyzed space.

Table 5 presents the variability of the WP considering the ranges of CO_2 levels by office typology, while Figures 17 and 18 graphically represent the results achieved.

In the study, a higher WP range amplitude is seen in OO compared to CO for an EqN equal to 5. The amplitude of this range allows identifying UW of OO with a greater adaptation capacity to values of up to 840 ppm (Figure 17), without their performance being affected. This range is lower for CO, admitting CO_2 levels that do not exceed 627 ppm (Figure 18).

Lighting level

The light comfort is measured in terms of illuminance levels on the work plane, without considering the source of lighting (natural or artificial). These are measured in Lux.

Table 6 presents the WP variability considering the lighting level ranges by office typology on the work plane, and Figures 19 and 20 graphically present the results achieved.

From the observation of the ranges, it stands out that the excellent level (EqN =5) has a different luminance with higher values in CO compared to OO. This characteristic has an average difference of 100lux (Figures 19 and 20).

The behavior of the data allows determining that the UW of OO can work optimally at lower lux levels, without their performance being affected, i.e. they have a higher capacity to adapt to darker work planes.

Open Office (OO)					
Qualitative evaluation	Excellent	Very Good	Good	Regular	Bad
EqN	5	4	3	2	1
Maximum [ppm]	<842	<953	<1064	<1175	-
Minimum [ppm]	-	842	953	1064	≥1175
Closed Office (CO)					
Qualitative evaluation	Excellent	Very Good	Good	Regular	Bad
EqN	5	4	3	2	1
Maximum [ppm]	<627	<700	<771	<843	
Minimum [ppm]		627	700	771	≥843

Table 5. WP ranges valuation (air quality impact) during summer in OO and CO. Source: Preparation by the Authors.

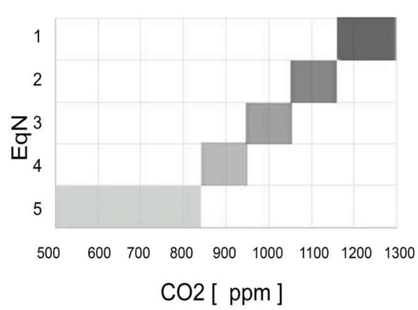

Figure 17. WP variability ranges, affected by air quality during summer in OO. Source: Preparation by the Authors.

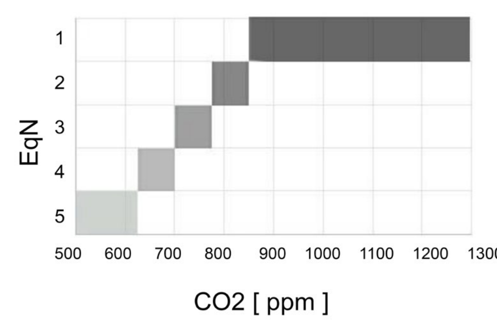

Figure 18. WP variability ranges, affected by air quality during summer in CO. Source: Preparation by the Authors.

Open Office (OO)									
Qualitative evaluation	Bad	Regular	Good	Very Good	Excellent	Very Good	Good	Regular	Bad
EqN	1	2	3	4	5	4	3	2	1
Maximum [Lux]	<210	<238	<325	<413	>500	>588	>675	>763	-
Minimum [Lux]	-	210	238	325	413	500	588	675	≥763
Closed Office (CO)									
Qualitative evaluation	Bad	Regular	Good	Very Good	Excellent	Very Good	Good	Regular	Bad
EqN	1	2	3	4	5	4	3	2	1
Maximum [Lux]	<243	<331	<419	<508	<596	<684	<773	<861	.
Minimum [Lux]		243	331	419	508	596	684	773	≥861

Table 6. Valuation of WP ranges (light impact) during summer in OO and CO. Source: Preparation by the Authors.

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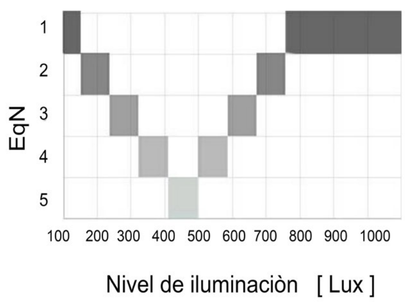

Figure 19. WP variability ranges, affected by light level during summer in OO. Source: Preparation by the Authors.

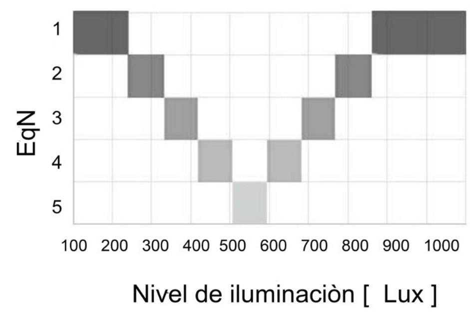

Figure 20. WP variability ranges, affected by light level during summer in CO. Source: Preparation by the Authors.

Open Office (OO)					
Qualitative evaluation	Excellent	Very Good	Good	Regular	Bad
EqN	5	4	3	2	1
Maximum [dBA]	<62	<67	<71	<75	-
Minimum [dBA]	-	62	67	71	≥75
Closed Office (CO)					
Qualitative evaluation	Excellent	Very Good	Good	Regular	Bad
EqN	5	4	3	2	1
Maximum [dBA]	<57	<61	<65	<68	-
Minimum [dBA]	-	57	61	65	≥68

Table 7. WP range valuation (of acoustic impact) during summer in OO and CO. Source: Preparation by the Authors.

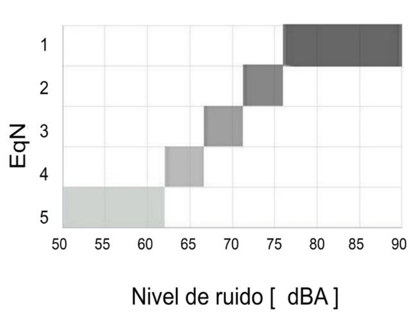

Figure 21. WP variability ranges, affected by sound level (dBA) during PVn in OO. Source: Preparation by the Authors.

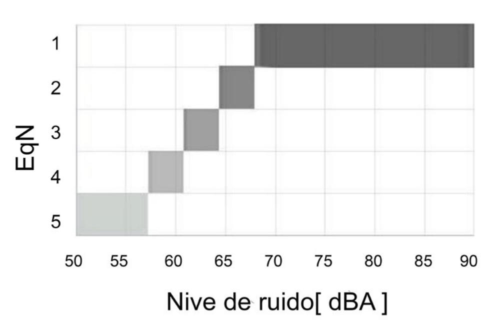

Figure 22. WP variability ranges, affected by sound level (dBA) during PVn in CO. Source: Preparation by the Authors.

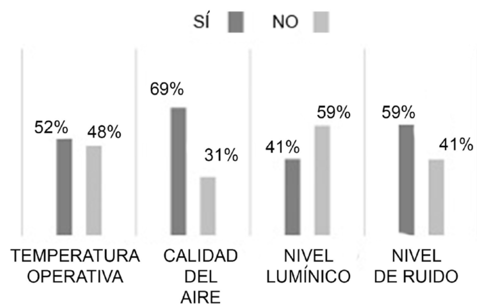

Figure 23. Level of impact of each variable on the individual WP and the resulting proportionality constants in OO typology. Source: Preparation by the Authors.

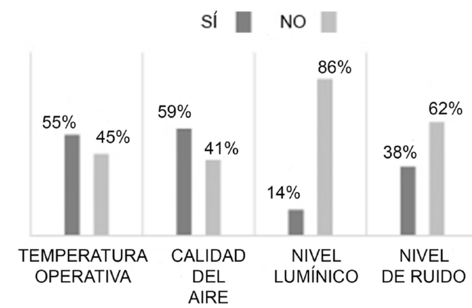

Figure 24. Level of impact of each variable on the individual WP and the resulting proportionality constants in CO typology. Source: Preparation by the Authors.

Noise Level

Sound comfort is affected by the noise level, when this is a sound that causes bother. It is measured in sound power (dBA, weighted decibel).

Table 7 shows the WP variability considering the noise level ranges by office typology, while Figures 21 and 22 graphically represent the results.

From the values found, it is detected that the ranges in OO have a higher amplitude compared to CO, with a difference of almost 5 dBA between both office typologies. As such, it is acknowledged that the UW of OO have a higher capacity to accept higher noise levels, without seeing their work performance affected.

Optimal work performance indicator

From the response to the question *"Do you think that this variable negatively affects your performance?"* in this study's survey, the total percentage of those that answer YES [%] and NO [%] are considered. This allows knowing the level of influence of each variable on the individual WP.

Considering the percentages obtained, proportionality constants are built, to compare the total of the variables as a whole and each one, with their weight in importance.

What is presented in Figure 23 leads to the construction of the OWPI for OO (see Equation 1).

$$\boldsymbol{IRLO = 0,23 \,.\, Eq_{VRt} + 0,31 \,.\, Eq_{VRa} + 0,19 \,.\, Eq_{VRi} + 0,27 \,.\, Eq_{VRr}}$$

What is presented in Figure 24 leads to the construction of the OWPI for CO (see Equation 2).

$$\boldsymbol{IRLO = 0,33 \,.\, Eq_{VRt} + 0,36 \,.\, Eq_{VRa} + 0,08 \,.\, Eq_{VRi} + 0,23 \,.\, Eq_{VRr}}$$

As can be seen, the order of influence of the variables changes for both typologies. However, in both cases the CO_2 concentration appears as the one with the greatest influence.

The value obtained in Equation 1 and 2 is qualitatively translated, following Table 3.

OWPI validation-application

The OWPI tool is applied in this section, on two real OO and CO typology office cases, to validate the results (Table 8 and 9).

Case A - OO:
Table 8 shows the data obtained from measurements for each environmental variable and their valuation (EqN), following Figures 15, 17, 19 and 21.

Type	People	C°	CO_2	Lux	Dba
OO	4	27	1190	810	74
Evaluation		Eq_ VRt=2	Eq_ VRa=1	Eq_ VRi=1	Eq_ VRr=2

Table 8. Environmental values measured in case A and their numerical evaluation by ranges. Source: Preparation by the Authors.

As a result, the following OWPI value is obtained:

$$\boldsymbol{IRLO = 0,23 \,.\, 2 + 0,31 \,.\, 1 + 0,19 \,.\, 1 + 0,27 \,.\, 2 = 1,50 \rightarrow Malo}$$

Case B - CO:
Table 9 presents the data obtained from measurements for each environmental variable and its evaluation (EqN) as per Figures 16, 18, 20 and 22.

Type	People	C°	CO_2	Lux	Dba
CO	1	24.5	550	495	53
Evaluation		Eq_ VRt=4	Eq_ VRa=5	Eq_ VRi=5	Eq_ VRr=4

Table 9. Environmental values measured in case B and their numerical evaluation by ranges. Source: Preparation by the Authors.

As a result, the following OWPI value is obtained:

$$IRLO = 0,33\,.4 + 0,36\,.5 + 0,08\,.5 + 0,23\,.4 = 4,44 \rightarrow Excelente$$

CONCLUSION

Connecting the self-reported work performance vote with the levels of each environmental variable studied, allows getting to know optimal values and the most vulnerable values of operating temperature, air quality, light level, and noise level, to achieve a good WP in UW in a warm template area during the summer period.

The construction of ranges evaluated through the EqN, reports the WP level of users by open and closed office typology, varying from 1 (bad WP) to 5 (excellent WP). Thus, the valuation of an OWPI equal or close to 5, as well as indicating the best environmental conditions for the optimal performance of the UW considering the health, assumes a "beneficial" contribution to comfort conditions (thermal, visual, acoustic and air quality) of the UW. On the contrary, an OWPI equal or close to 1 indicates to the Building Manager about the need to address comfort related environmental solutions, and as a result, of the WP in the work setting.

Regarding the comparison between office typologies, it is confirmed that the UW develops a higher level of environmental adaptation in OO, so that said offices are a less advantage space on having a lower occupation factor, lack of windows, lack of total enclosure, and higher noise levels.

Finally, it highlights that the development of the OWPI tool characterizes WP conditions in offices for warm template climate regions during the summer. In future research, the idea is to extrapolate this progress for winter and transitory periods, as well as how to apply them in other local case studies.

LIST OF ABBREVIATIONS

CAI Calidad Ambiental Interior
CO2 Dióxido de Carbono
EqN Equivalente Numérico
IRLO Indicador de Rendimineto Laboral Óptimo
OA Oficina de Tipología Abierta
OC Oficina de Tipología Cerrada
RL Rendimiento Laboral
UMM Unidad Móvil de Medición
UT Usuarios-Trabajadores
VR Voto de Rendimiento
VRa Voto de Rendimiento de la Calidad de Aire
VRi Voto de Rendimiento del Nivel de Iluminación
VRr Voto de Rendimiento del Nivel de Ruido
VRt Voto de Rendimiento Térmico
Eq_{VRt} Equivalente Voto de Rendimiento Térmico
Eq_{VRa} Equivalente Voto de Rendimiento Calidad de Aire
Eq_{VRi} Equivalente Voto de Rendimiento de Iluminación
Eq_{VRr} Equivalente Voto de Rendimiento de Ruido

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MINGA: SUSTAINABLE AND REPLICABLE URBAN RENOVATION MODEL, THE BUENAVENTURA CASE

MINGA: MODELO REPLICABLE DE RENOVACIÓN URBANA SOSTENIBLE, CASO BUENAVENTURA

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RESUMEN

Este artículo presenta los resultados obtenidos en la investigación realizada durante la ejecución de un diseño de renovación urbana sostenible en la ciudad de Buenaventura, Valle del Cauca, Colombia, como parte de la propuesta del equipo MINGA para el SDLAC 2019 (Solar Decathlon Latin America and Caribbean). Este proyecto fue desarrollado por un grupo de estudiantes y profesores, dentro de los espacios académicos de los programas de pregrado de Arquitectura e Ingeniería Civil de las universidades partícipes del equipo MINGA. Se utilizó la metodología de enseñanza-aprendizaje basada en proyectos, con integración curricular en cursos interdisciplinares tipo taller de proyectos. El objetivo principal fue demostrar la viabilidad de un proyecto de urbanismo resiliente, concebido para el clima futuro en una ciudad costera del trópico cálido-húmedo. Los resultados demostraron que se puede crear un urbanismo climático, resiliente al clima, que garantice la permanencia de los habitantes originales de las zonas costeras, mitigando los riesgos por inundación y garantizando el arraigo cultural de sus habitantes, aun en escenarios de aumento en el nivel del mar

Palabras clave
urbanismo sustentable, cambio climático, vivienda social

ABSTRACT

This article presents the results obtained in research made during a sustainable urban renewal design in the city of Buenaventura, Valle del Cauca, Colombia, as part of MINGA team's proposal for SDLAC 2019 (Solar Decathlon Latin America and Caribbean). This project was developed by a group of students and professors, as part of the undergraduate programs of architecture and civil engineering of the partner universities in the MINGA team. A project-based teaching-learning methodology was used, integrating the curricula in interdisciplinary project workshop-type courses. The main goal was to demonstrate the viability of a resilient urban planning project, conceived for the future climate in a coastal city in the hot-humid tropics. The results showed that a climate-resilient urbanism can be created, which guarantees the permanence of the original inhabitants of the coastal areas, mitigating flooding risks, and preserving the cultural roots of the inhabitants, even under sea-rise scenarios.

Keywords
sustainable urbanism, climate change, social housing

INTRODUCTION

The Solar Decathlon is currently the most important international sustainable construction academic event. Held since 2002, it states among its goals, the education of students and the public regarding the environmental benefits that sustainable construction provides (Kos & De Souza, 2014). The Latin American editions of the competition, held in Cali, are pioneers in focusing attention on sustainable housing solutions for low-income neighborhoods, with a regional relevance for the tropics (Herrera-Limones, León-Rodríguez & López-Escamilla, 2019). For the 2019 edition, an alliance was made between the Pontifical Xavierian University – Cali (Colombia), the Federal University of Santa Catarina, and the Federal Institute of Santa Catarina (Brazil), forming an interdisciplinary team comprising students and professors from architecture, engineering, visual communication design, and communications. The Minga team designed, built and set up a housing prototype that is part of an urban multi-family housing project for the city of Buenaventura. Although the urban proposal is located on a specific site, bearing in mind the environmental, social and economic conditions of the city and the region, using a project that meets the population's needs, it is adaptable to other regions with similar coastal conditions in the warm-humid tropics.

The planet's urban coastal areas are the most vulnerable when it comes to the negative effects of climate change, on being highly populated, and having a higher population growth projection (Béné *et al.*, 2018; Neumann, Vafeidis, Zimmermann & Nicholls, 2015). In these regions, and particularly in Latin America, there are high rates of poverty, exclusion, inequality and housing precariousness, which make life on the coasts, a very high risk option (Nicholls *et al.*, 2014; Vergel Tovar, 2010). All this outlines new challenges for coastal cities: making them more viable and suitable for future climatic conditions, prioritizing the protection of their inhabitants, and protecting infrastructure against the negative effects of climate change, using adaptation strategies that foresee events, and reduce vulnerability (Hernández-Guerrero, Vieyra-Medrano & Mendoza, 2012).

Facing the new challenges, methodological approaches become necessary, that are capable of developing climate-proof urban models (Wardekker, De Jong, Knoop & Van Der Sluijs, 2010), which focus on climate urbanism as a new paradigm beyond the concept of sustainable urbanism (Long & Rice, 2019). It is under this scenario of charge that the concept of urban resilience gains strength, understood as the capacity of a system to maintain or quickly revert to its desired operation after a disturbance (Meerow, Newell & Stults, 2016). It is necessary that urban systems increase their adaptation capacity, preparing a suitable response to current and future challenges (Hernantes, Maraña, Giménez, Sarriegi & Labaka, 2019).

The case study also outlines the challenge of acting on the informal city. Traditionally, large urban projects provide an answer to a physical setting that needs to be transformed, but rarely do they consider the true needs of their inhabitants (Hernández Araque, 2016). Thus, design processes must be developed with community participation, offering "locational" responses, suitably fitting the specific contexts (Musango, Currie, Smit & Kovacic, 2020). The proposal presented here, suggests that it is possible to prepare a resilient urban renewal model, that minimizes forced displacement within the city, and that slows down urban expansion, through a project that considers current and future climate conditions, sociocultural conditions, and that reinterprets the occupation systems of ancestral lands, using new construction technologies and innovative design processes.

CONTEXTUALIZATION

Buenaventura is a coastal city in southeastern Colombia (3°52′59′′ North, 77°4′1′′ West). With its strategic position, its connection to the Pacific Ocean, and its proximity to the Panama Canal, it is home to one of the country's most important ports. The city is divided into two: the continental section, and the island of Cascajal, connected by the city's main road, Avenida Simón Bolivar. This relationship with the sea is a very important aspect for the economy, the environmental wealth, and the culture of the city. Despite this, due to political reasons, the economic revenues are not reflected in the city infrastructure. It is for this reason, that the living conditions of inhabitants are often precarious.

According to the Köppen-Geiger climate classification, the climates of Colombia are type "A" which correspond to tropical humid ones. Specifically, Buenaventura has an "Af" tropical rainforest climate, with high temperatures -around 30°C- and very small variations throughout the year, abundant rainfall (150-1000 cm), fairly cloudy, and with a high humidity (Rafferty, 2009). Thanks to its location, the city has a great diversity and natural wealth. Although it has a relevant number of species of flora and fauna, at an urban level it lacks space with suitable environmental conditions. Urban sprawl has been projected in the Regional Organization Plan (POT, in Spanish) (Buenaventura Mayor's Office, 2001), perpetuates deforestation and considers the use of many important ecosystems for this purpose, like the mangrove swamps (Figure 1).

With an estimated population of 440,995 inhabitants (DANE, 2005), considering both the rural and urban area, the communes (areas) with the highest density are located along the southern edge of the island -especially 3 and 4- (Figure 1), which have informal overcrowded settlements with a high number of people per dwelling, in just a few square meters. Most of the

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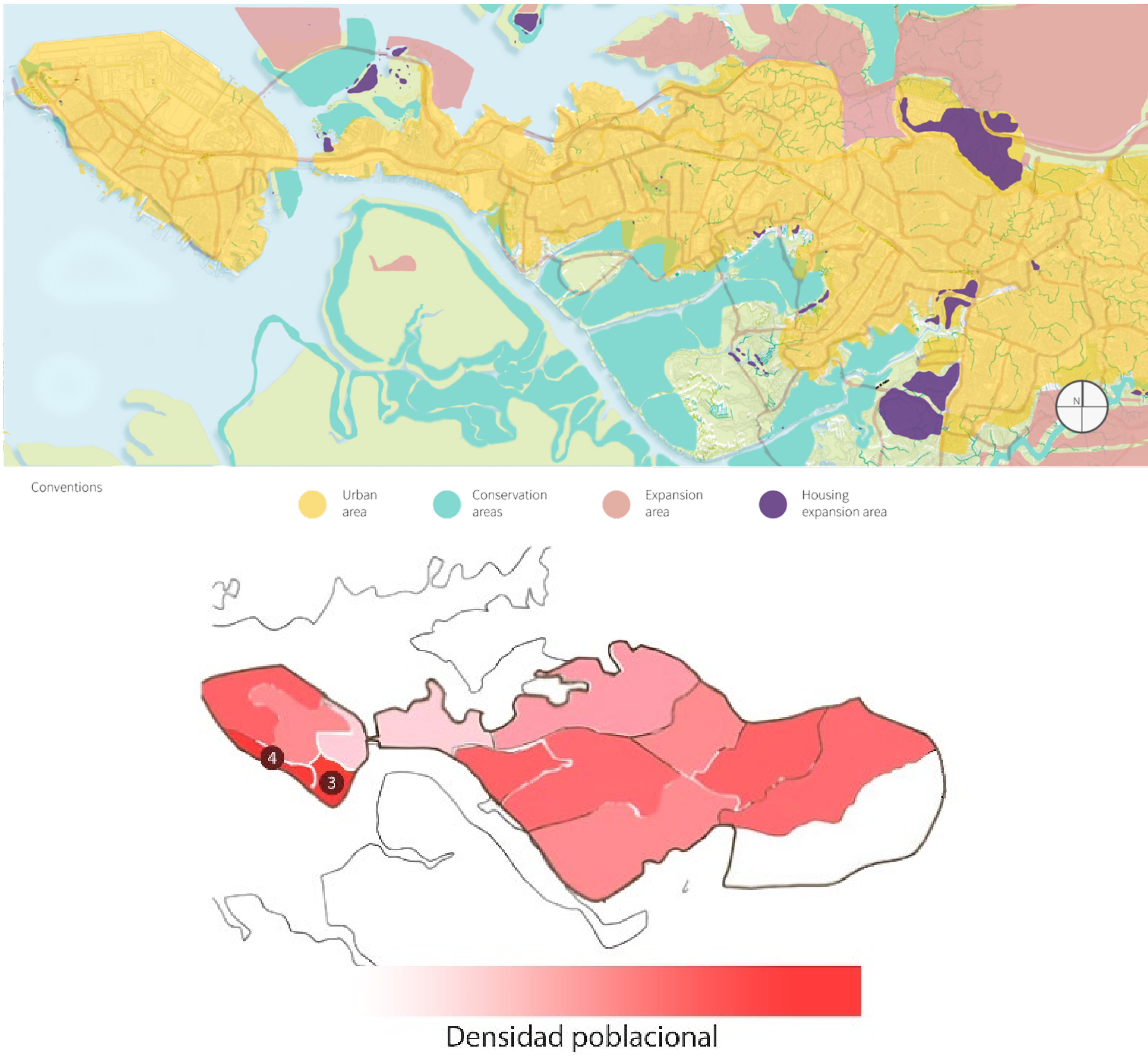

Figure 1. Expansion areas / Populational Density of Buenaventura. Source: Prepared by the Authors.

municipality's homes with Unsatisfied Basic Needs (UBN) and poverty are concentrated in this sector of the island (DANE, 2020). In fact, in Buenaventura, more than 15% of the population do not have basic services (DANE, 2018), and these areas are within those most affected in this sense. In addition, the levels of violence are higher in these communes than in the rest of the city.

Added to this, different social and economic issues affect the community, including: forced displacement, a lack of equality and work opportunities, limited access to education and health, illiteracy, illegality, etc. (Martínez *et al.*, 2013). In 2013 alone, more than 13,000 people were forcibly displaced to the city (Schoening, 2014), which may explain the growing development of informal settlements, especially along the edge of the island, which have grown towards the ocean, with precarious conditions, on lacking resources for their inhabitability.

In this way, the shoreline of Cascajal Island mainly comprises refill used by the inhabitants to gain land from the ocean, expanding its urban boundaries. A traditional construction system is used for this: stilts (Figure 2). In this, the stilts (hardwood palm trunks) are driven into the seabed, to set a base made from the same wood, to build on this, then refilling underneath using waste material. This causes great contamination to the sea, and puts those settling there in danger, due

Figure 2. Existing structures in the study area. Source: Prepared by the Authors

to the high flood risk there is on the southern part of the island and the western part of the continental area (Figure 3). Likewise, the lack of planning has generated deficiency or absence of water and sewerage systems, among other deficient or non-existent systems.

Similar cases have been studied at a regional level, like that in Morelia (Mexico), as flooding events can be associated to the way the city is conceived. Its lack of planning and a clear response from the authorities, demonstrates that the socioeconomic differences compared to those living in the periphery (as also happens in the case of the Bonaverense community) reflects a notorious "risk inequality". Because of this, the notion of adaptability that the MINGA project and the case study in Morelia seek to show, becomes a kind of euphemism of "social justice" (Hernández-Guerrero *et al.*, 2012).

The World Health Organization states that "green" and "blue" public spaces can greatly improve mental and physical health, and people's quality of life, reducing stress levels, comorbidities, and providing spaces for rest, leisure and physical activity (World Health Organization, 2016). Currently, Buenaventura has a public space index of 0.51m^2 per inhabitant, represented by a lack of public parks, well below the cities that were subject of the aforementioned study. On the other hand, regarding the road system, Avenida Simón Bolivar is a main road that communicates the city with the rest of the country. A road is projected on the north side of the island that will be built with a more commercial and heavy transportation purpose, which will revitalize this area of the city and will consolidate the south as a residential and light transportation area. Thus, the MINGA team understands the variables of the context, and has taken the decision to mainly work on the shoreline of Cascajal Island, and in a sector along the coast of the continental area.

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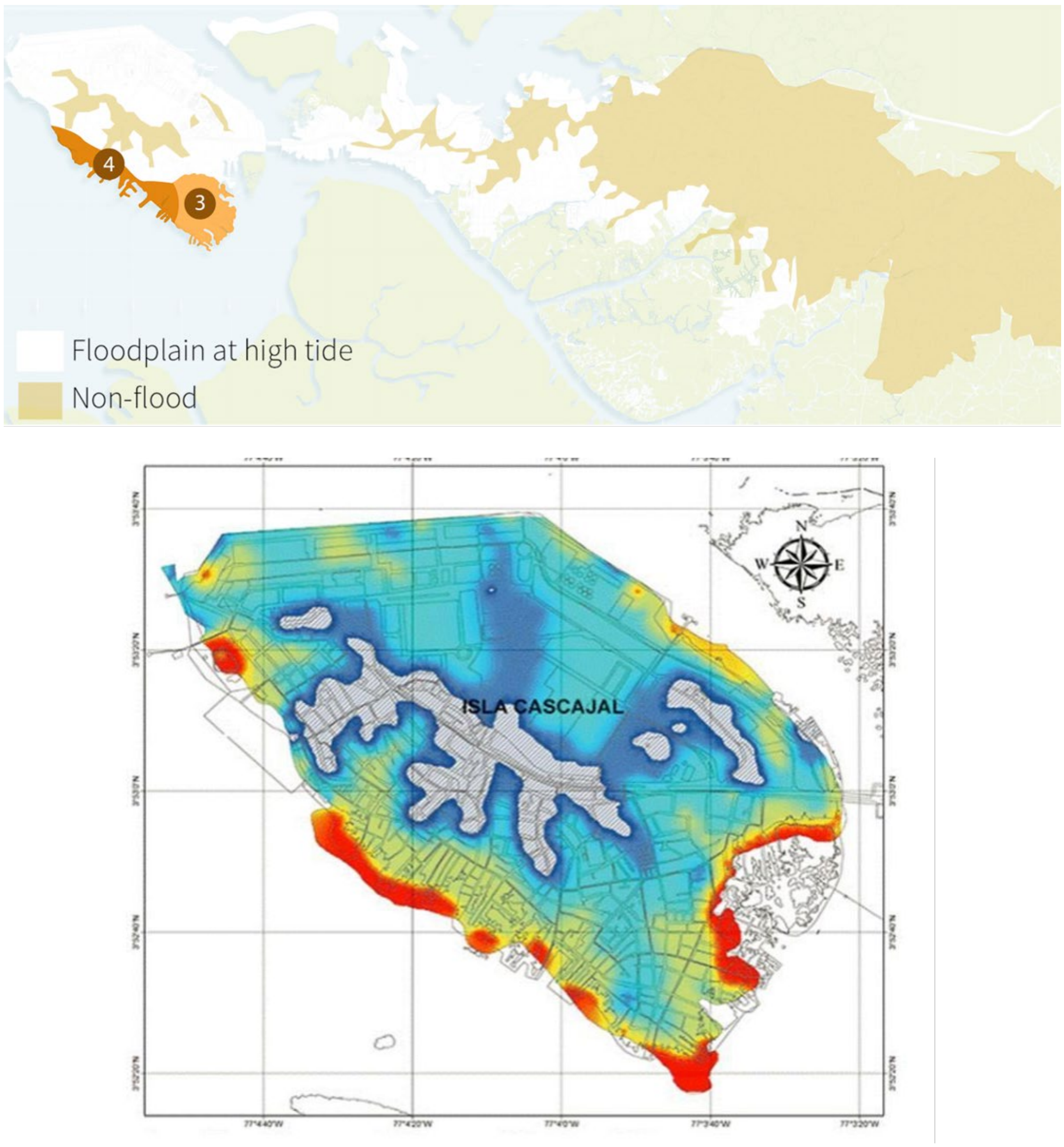

Figure 3. Flood map of Buenaventura and Cascajal Island.Source: Left: Preparation by the Authors. Right: Cocuñame & Salcedo (2017, p. 200).

METHODOLOGY

Considering the guidelines of the competition, the urban proposal of MINGA was made by integrating the topics of the Solar Decathlon into the courses of the final years of the undergraduate Architecture and Civil Engineering courses of Xaverian – Cali and UFSC, courses where a project based teaching-learning methodology was implemented, which allows students to put into practice, the theoretical knowledge acquired in traditional courses (Herrera-Limones, Rey-Pérez, Hernández-Valencia & Roa-Fernández, 2020; Jin *et al.*, 2018; Osuna-Motta, 2018). With this approach, the research, made by more than 80 students and 12 teachers from Colombia and Brazil, focused on the issue of mid density urban design applied to the context of the Latin American tropics, to achieve an innovative proposal inspired by

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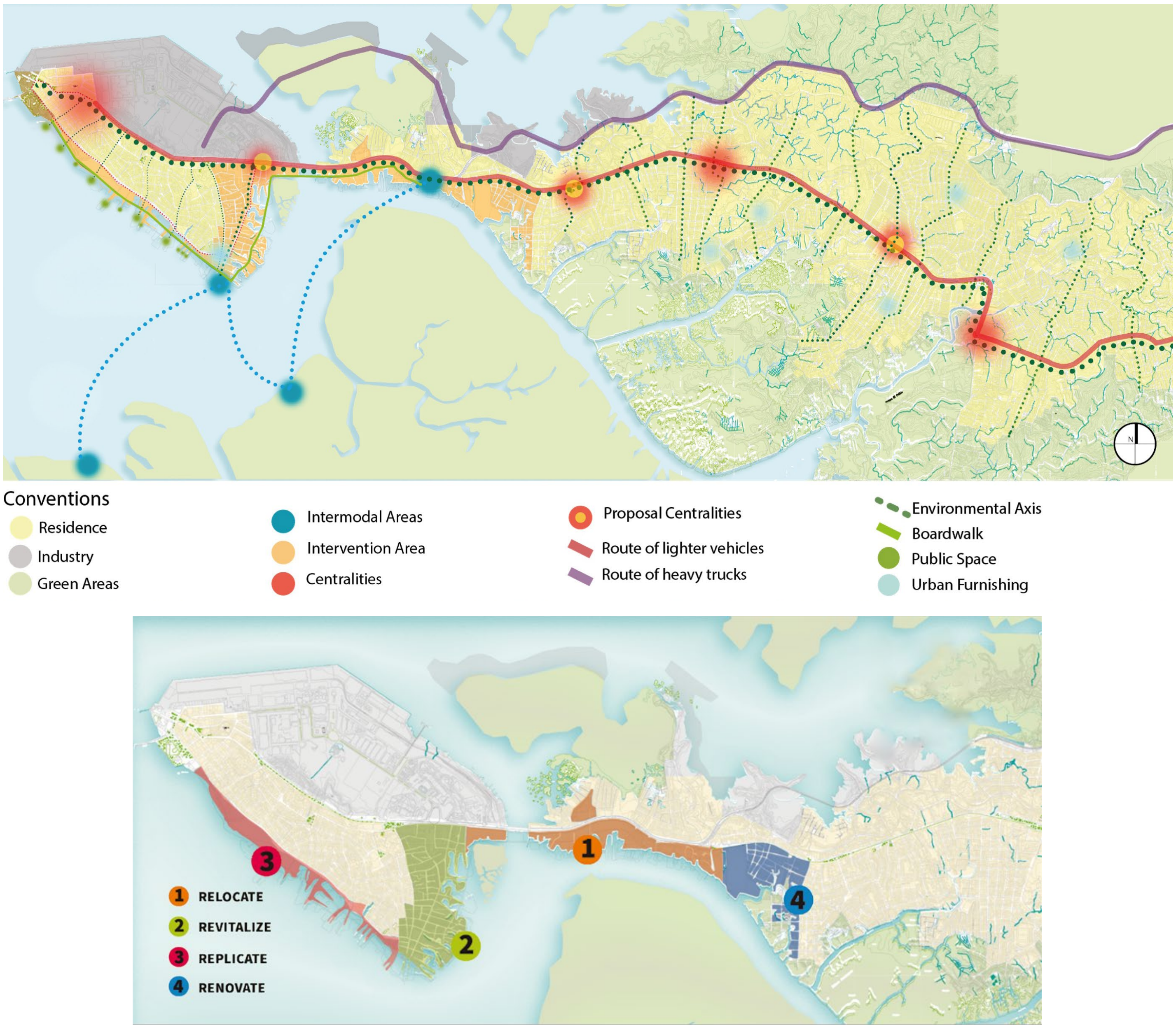

Figure 4. Urban Master Plan. Proposal of MINGA – 7 Phases of the Project. Source: Prepared by the Authors

low cost social housing, that is sustainable to climate conditions over the next 50 years. The process was the following:

1. Analysis and research about the territory was made, addressing the environmental, historic, social and economic, highway, morphological, public services, regulatory, uses and facilities, and risk conditions.
2. It began with a basic outline, moving from a macro to a micro scale, identifying which were the places in the city with the most risks and critical conditions, to work on these within a master plan.
3. Then, an Urban Master Plan was outlined, which comprised both the continental area and Cascajal Island. It considered 3 phases where relocation strategies for the inhabitants of the areas being affected were included, along with the design of roads and areas to intervene (both for housing development and for public space and equipment). The scale of the site was also developed in greater detail, covering several blocks in the southern sector of the island, replicating the housing prototype in high-rise buildings.
4. Finally, a housing prototype was made which was built to real scale to demonstrate its operation, along with a 1:250 scale model that shows the housing units that form high-rise buildings designed for the urban plan, as well as some of the public spaces and the proposal vis-à-vis the road design.

Figure 5. Localization and scale proposal. Source: Prepared by the Authors.

RESULTS AND DISCUSSION

A feasible urban renewal proposal was prepared, in a sector where the municipal authorities had planned an eviction process due to the high flood risk in the area. The measure, which does not consider mitigation alternatives to keep the inhabitants where they are, would uproot a population that economically and culturally depends on their relationship with the sea. The model is explained below, using the scales it was based upon: from macro to micro.

URBAN MASTER PLAN

Beginning from the large scale, the urban proposal of MINGA seeks, starting by understanding the context, to generate strategies to solve the different problems of the Bonaverense community. One of the first ones consists of generating two important road links between the island and the continental area: the first would be the one proposed by POT, to the north of the city, that would carry the heavy traffic, and would serve as a commercial link for the city. The other would be the wharf, which will be detailed later on, designed to provide the public space that the city lacks and with several clean transportation options.

In the same way, different already existing routes would be recovered to use them as environmental hubs: first, creating a large green separation along Avenida Simón Bolivar (Av. SB), which crosses the entire city. Second, several important links would be placed along this avenue, with the idea that these become secondary environmental hubs, and end up mainly being recreational public spaces. Third, alongside the wharf, 1st street (Calle 1ra) that runs to the west of Avenida Simón Bolivar to the east of the island, would be fitted out, running alongside the shoreline and linking up with Highway 20 (Carrera 20), which runs to the east side of the main avenue (Simón Bolivar). This road would be available for light transportation, other means of transportation that are already used, like private vehicles, taxis, buses that already circulate in the city, etc. (Figure 4).

At a local scale, the project would be done in 4 phases (Figure 5):

1. Relocation: in this stage, the intention is to connect the island with the continental area of the city, generating public and commercial space alongside Piñal bridge, the only road infrastructure that connects the island with the continent currently. At the same time, the population of the area intervened would be relocated initially, temporarily relocating them in the continental part of the city, leading to the second phase.
2. Revitalization: this would seek to revitalize the first area being intervened, on two fronts: the public, with the section corresponding to the wharf, along with the projected public spaces and equipment; and the private, with the construction of residential areas.
3. Replication: the wharf would be connected to the existing one and all the urbanization model would be replicated along the southern and western shorelines of Cascajal Island, linking this to the continent. This is a triggering action that can foster and promote proper urbanization towards the south, and the consolidation of this residential area with the public space that it requires.
4. Renewal: this last phase would consolidate the urban renewal project, connecting the entire edge of the island with the continental area.

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Figure 6. Urban cross-section of the proposal and the factors to promote. Source: Prepared by the Authors

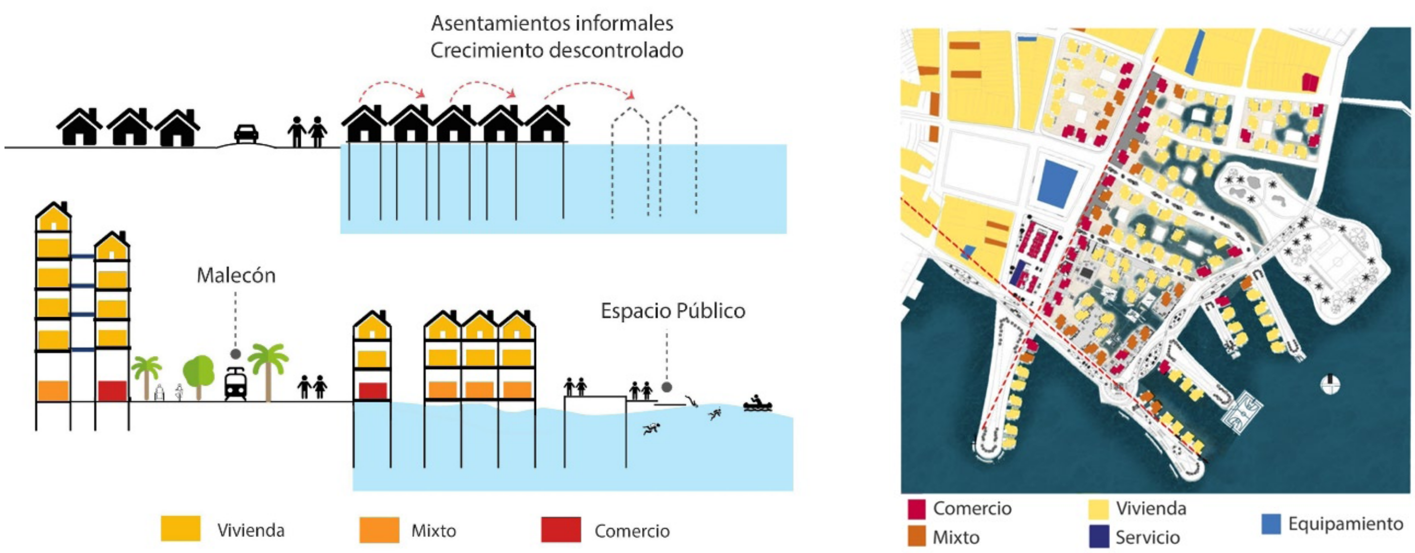

Figure 7. Proposed height and uses. Source: Prepared by the Authors.

LOCAL SCALE

Sustainable use of resources

First and foremost, the intention is to reuse existing land and urban structure, to not generate interventions that damage the region, especially the uncontrolled growth towards the ocean and the deforestation of the mangroves, favoring a more compact, less extensive urban structure (Urriza & Garriz, 2014). Then, due to the important relationship that Buenaventura's inhabitants have with the sea, different economic activities are considered within the urban design, which emerge from this water body, such as: fishing, a different route to land to move between adjoining areas and the continent, as well as its connection with the traditions of the inhabitants and their cultural connotation. Third, the implementation of new mechanisms to supply energy is done on two scales. At a macro scale, using renewable energy sources for public spaces, as well as the implementation of an electric tram for public transportation. At a micro scale, this seeks to replicate the photovoltaic system used in the housing prototype, along with the rainwater collection system and smart sensors to control the consumption of each housing unit.

It is worth adding that, on both scales, the possibility of generating other renewable energy options exists, like wind, tidal and wave power.

Sustainable use of the built space and urban activities

Following MINGA's slogan, "Sustainable Communities", three factors to strengthen the urban project process in Buenaventura were defined: nature, tourism and trade (Figure 6). Using these three dimensions, a mixture of uses is promoted in the project, without losing the main goal of developing an urban sustainable housing model. In the same vein, these are considered to encourage the respective sectors of the economy and to regenerate the public spaces of the city, promoting it as a tourist and economic destination in Colombia, and balancing, as a result, the quality of the residential sector. At the same time, sustainable communities are expected to be generated, preserving the cultural values of the population.

In this way, the generation of the different uses allows for greater citizen accessibility considering their needs, reducing transportation distances and times. It is for this reason, in the project's public layout, it proposes placing

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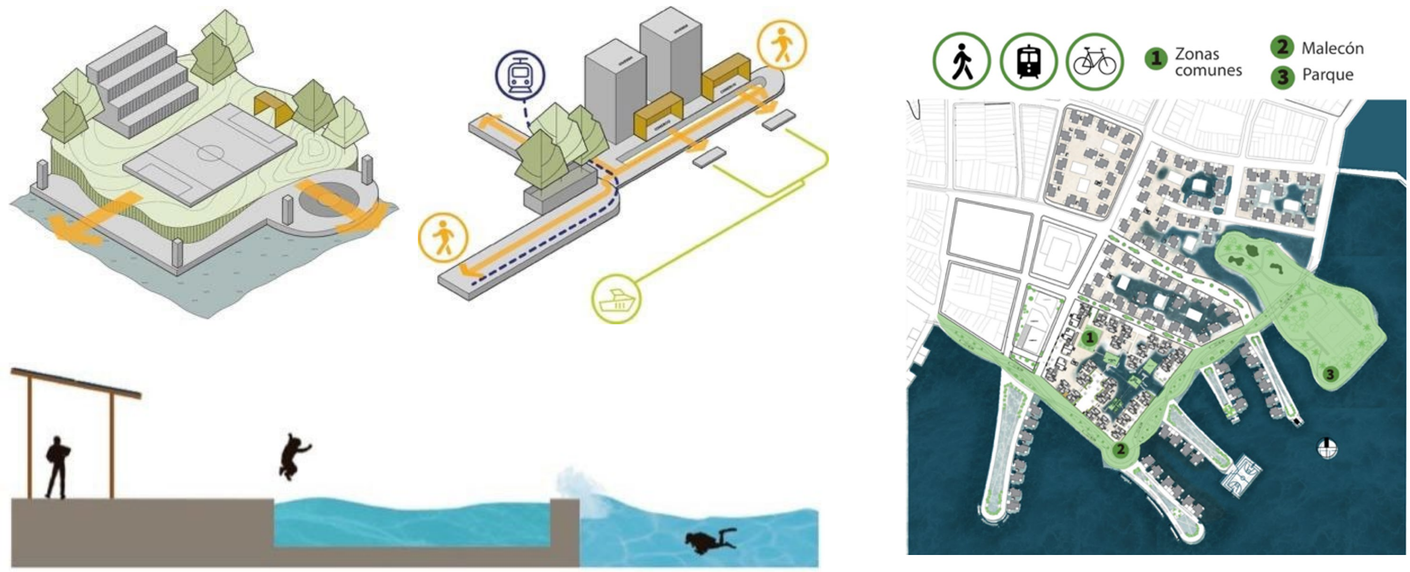

Figure 8. Design of public spaces / adaptability and floodability. Source: Prepared by the Authors

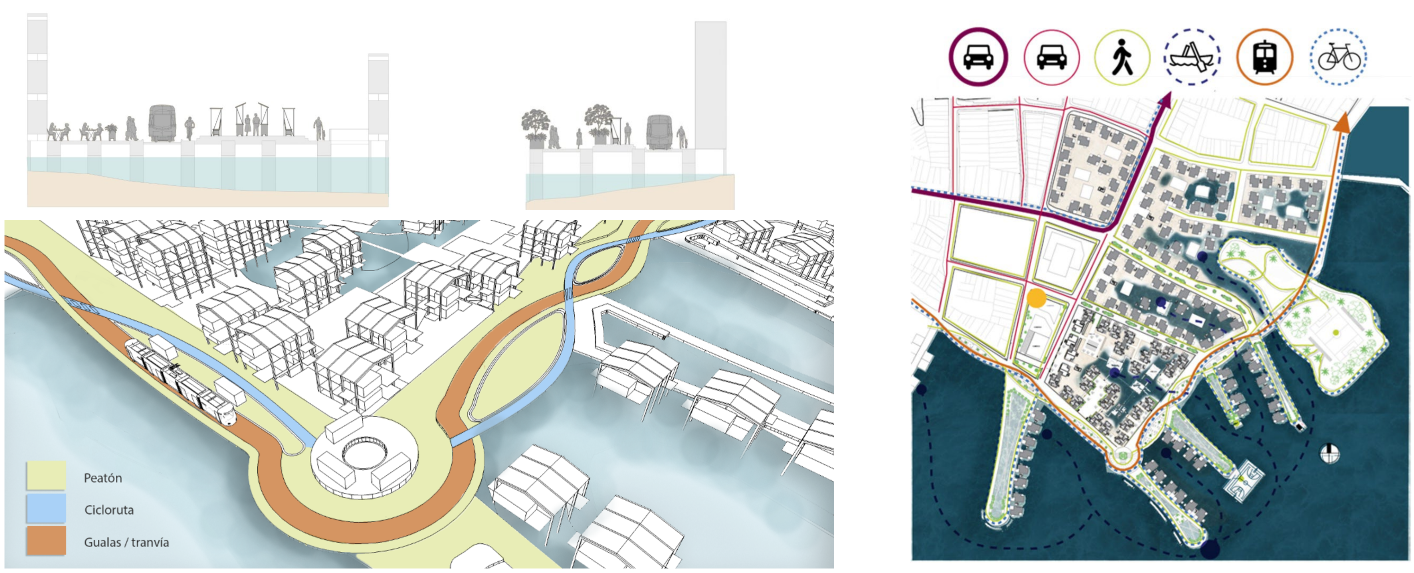

Figure 9. Sustainable mobility proposal / Wharf.Source: Prepared by the Authors.

commercial units alongside the main vehicle and pedestrian routes (which includes the wharf), conserving the privacy of the housing and its common areas within the blocks. Along this same line, as the high-rise densification allows for a greater capacity of inhabitants on a smaller portion of land, it was decided to build high-rise blocks that do not exceed 6 floors or that are under 3 floors. In this way, the buildings are laid out so that their height drops as they approach the sea (Figure 7).

effective public space and development of facilities

The shortage and lack of public space in Buenaventura shows the need to design effective public spaces that give inhabitants more quality spaces, that are more extensive, accessible and better designed. Thus, the use of the unbuilt land is proposed, to generate public areas there, equipped with playgrounds, spaces for physical activity and, where possible, green focal points for the city. These areas are designed to be flood resilient, i.e. so that they adapt to sea rises and where possible, mitigate the impact of possible natural disasters, something that the wharf also looks to do (Figure 8).

sustainable transport and accessibility

To improve and facilitate connection between Cascajal Island and the continental part of the city, a wharf was designed, where the plan is that different forms of clean transportation converge (Figure 9). The design is laid out using a single surface, marking each area out for its respective user, with the goal of democratizing the space, and fostering a culture where the pedestrian is privileged, while giving room for the rest of the means of transportation.

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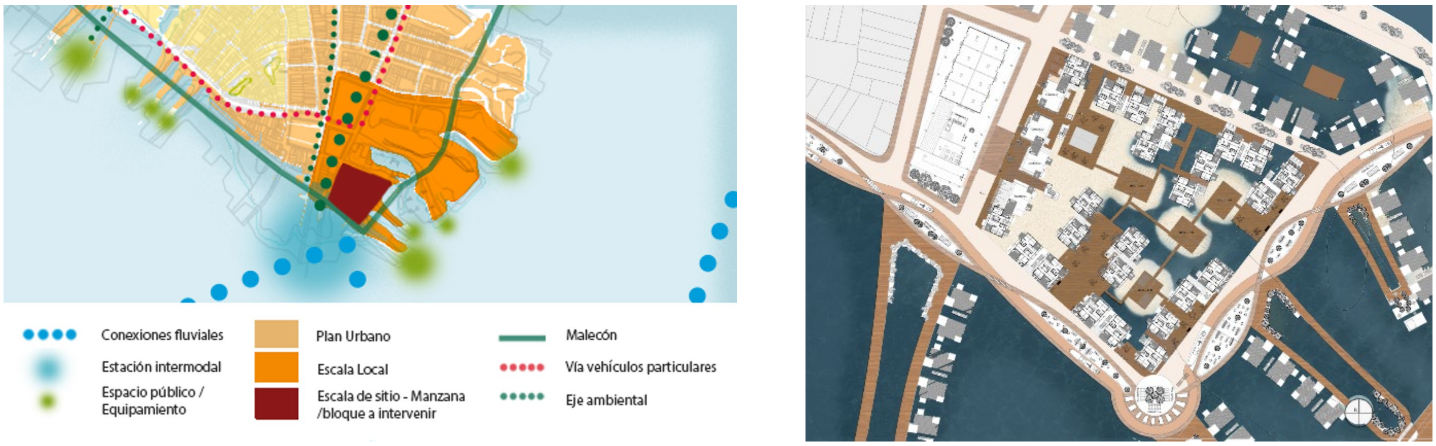

Figure 10. Localization and block plan designed at a site scale. Source: Prepared by the Authors.

Initially, a road will be destined for the traditional ATVs, the most commonly used informal public transportation on the island, formalizing them, and seeking their future transition to a tram as a clean transportation system. A path will also be assigned alongside this, as a cycle path, and another large part for pedestrians, the latter alongside the sea. As an additional solution, understanding the different means of transportation of Buenaventura, a road is included alongside the wharf, which would also cross the entire island, connecting it to the continent, where the flow of vehicles and motorcycles would be.

SITE SCALE

For the urban project, the SDLAC 2019 contest, proposed the in depth development of a block in greater detail. Thus, the MINGA team chose a block to the south of Cascajal Island (Figure 10), in commune 3, an area where different activities converge, which will allow connecting the island to the continental section. The importance of understanding, how the city is conceived for its inhabitants, the characteristics of the urban development and their ways of life, was highlighted. The following goals were set out using this:

- Solving the high demand of effective housing caused by the growing population density on the island. Beginning with communes 3 and 4, where there is a higher number of informally built dwellings, so that it is densified in high-rise, freeing up more common and public space on the ground level, where a density of at least 120 dwellings per hectare is proposed.
- Reaching a balance between the density of inhabitants and the effective public space, improving and maintaining the life in community.
- Fostering the relationships there already are with the sea, so that these are not lost despite the change regarding the means of building the dwelling.
- Designing a sustainable housing model, which considers the possibility of housing up to 8 people in two independent housing modules, considering the way of life of Bonaverense families, where it is common to find more than one nuclear family per dwelling. In addition, it must be economically feasible, without exceeding the maximums of the subsidy policies for social housing in Colombia, making the project accessible to the target population.
- Including common areas to bring the community together, which can remain while the tide is low, be floodable when it rises, and that it is a means of connection and transportation with the sea.
- The common areas for circulation in buildings will be points to foster meeting as an "extension" of the private areas, favoring life in community.
- Making use of renewable energies.
- Having a structural design in line with a resilient building typology, which allows counteracting the possible effects of climate change and the resulting rise in sea levels (Figure 11).
- Setting aside some street level housing units for adaptation to small stores, a practice commonly seen in this sector of the city.

CONSTRUCTION SYSTEM: REINTERPRETATION OF THE TRADITIONAL STILT CONSTRUCTION

A reinterpretation of the stilt housing typology was made, with a novel structural system in Colombia, made from glued laminated wooden colonnades, replacing the traditionally used mangrove wood, which allows building multi-family buildings of up to six floors. With this, the impact of deforestation of these ecosystems is reduced. On the other hand, it seeks to minimize the risk of flooding from tides in the current and future climate, and stop the informal growth of the island through high-rise densification of an urban area, alongside the design of public space and equipment along the island's shoreline.

VIABILITY: SUBSIDY AND FINANCING POLICY

The VIS or Social Housing policy in Colombia has a subsidy system for the demand. This policy seeks to increase the effective demand of social housing through subsidies

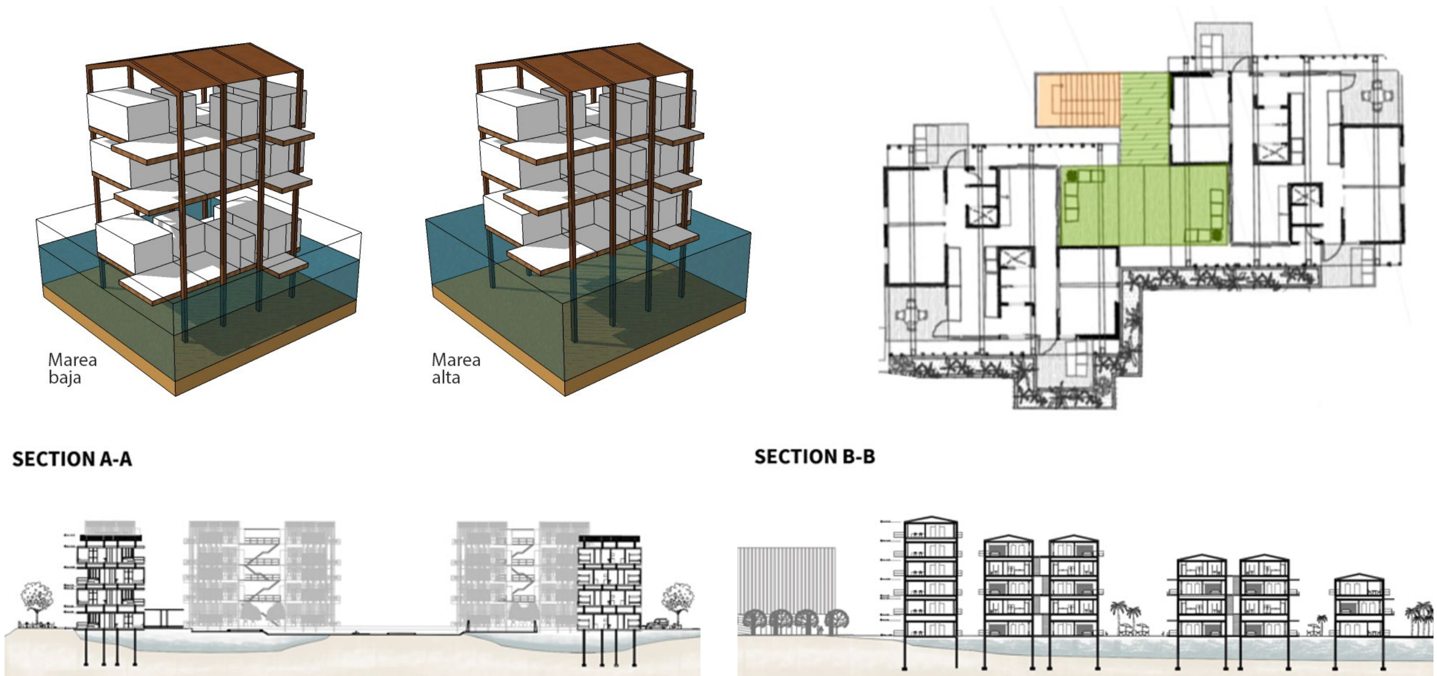

Figure 11. Floatability layout, standard floor plan, and cross section of the dwellings. Source: Prepared by the Authors

to beneficiaries, which are complemented with soft and savings loans, so that families with fewer resources can access their own home. The value granted to the beneficiary families, depends on the range of family incomes and the total cost of the dwelling. To promote the development of urban renewal projects, the national government increased the maximum subsidy for social housing up to 175 SMMLV (Current Legal Monthly Minimum Salaries) which for 2020, is the equivalent of 153,615,525 COP (Colombian Pesos), approximately US$41,794 to July 27th, 2020.

The MINGA multi-family project for Cascajal Island involves housing complexes of up to 6 floors, reaching a density of 127 dwellings per hectare, each one with an option to house up to 2 nuclear families (maximum of 8 people), with high standards of access and quality public and collective spaces. This is done, using industrialized prefabrication and building systems, and local materials. The initiative, to fall within this price range, outlines strategies that foster improving the quality in the urban conditions of the intervention area, with the following conditions:

- It promotes densification of the area with an integrated project that guarantees the construction of public equipment, complementary services and spaces.
- It guarantees the suitable and efficient provision of household public services.
- It foresees an appropriate use and management of the environment and natural resources.
- It promotes the protection and integration of environmental protection and conservation areas, following what is defined in the POT.
- It articulates social housing with infrastructure for the road transportation system.
- It promotes and generates accessible networks for people with disabilities and difficulties with locomotion by eliminating physical barriers.
- It improves the qualitative standards of public space, seeking to increase the quality, provision and a better use of the existing public spaces.
- It guarantees collective equipment systems that cover the needs of the new population that are incorporated to the area.
- It incorporates determining factors of risk prevention and management in a sector that the regional regulatory plan has identified as a high or medium mitigable risk.

CONCLUSIONS

With the results of the MINGA project, the viability of the strategies proposed for the renovation of shorelines in coastal cities of the topics is shown, though low-cost high-rise housing, with a habitational density that suitably uses the existing urban infrastructure, managing to stop the urban sprawl of the cities, dealing with a very sensitive issue in the coastal cities of Latin America and the Caribbean (Barragán & De Andrés, 2016). The project achieves high standards of sustainability, given that its construction cost allows that it is subsidized within the VIS policy in Colombia. This type of sustainable housing generates a lower cost for the users through its service life, as it reduces the value of public services, thanks to the use of photovoltaic solar energy, rainwater and the economic usufruct of the property, providing a module as a store, or from its rental, as a second housing unit of the home.

To conclude, although the urban proposal is located in the city of Buenaventura, Colombia, and bearing in mind its environmental, social, and economic conditions, the projected strategies used are adaptable to other regions with similar conditions. Thus, the urban renewal model is replicable in any coastal city with a warm-humid tropical climate, as long as the differences regarding conditions are considered, adapting to the context where this is implemented: considering the risk levels, the relationships with the urban structure there is, the characteristics of the population, and the housing policies of the local governments.

All in all, the feasibility of developing sustainable urban renewal is shown, and the importance of generating urban projects that respond to communities' needs is revealed, understanding the relationships that these have with their surroundings, as well as seeking solutions that understand the specific aspects of the territory in question.

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APPLICATION OF THE "FOOTPRINT FAMILY" FOR THE ENVIRONMENTAL EVALUATION OF PUBLIC BUILDINGS IN SPAIN. CASE STUDY: EDUCATIONAL CENTER.

APLICACIÓN DE LA "FOOTPRINT FAMILY" PARA LA EVALUACION AMBIENTAL DE EDIFICIOS PUBLICOS EN ESPAÑA. ESTUDIO DE CASO: CENTRO EDUCATIVO.

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RESUMEN

Dentro de los compromisos de la Agenda 2030, destacan los objetivos socioeconómicos para un desarrollo sostenible del conjunto de la sociedad, que plantean minimizar el impacto producido por la Administración Pública sobre el medio ambiente en todas sus actividades. Por ello, la creación y reforma de sus infraestructuras, necesarias para su funcionamiento y los servicios que presta, supone un gran impacto. El objetivo del presente trabajo se centra en una adaptación metodológica para evaluación ambiental de las obras promovidas por entes públicos, cuantificando y localizando los focos de impacto para poder tomar las medidas que los minimicen. Para ello, se proponen como indicadores la familia de las huellas, ecológica, de carbono e hídrica, caracterizadas por la simpleza del mensaje y la facilidad para implantarse en el sector de la construcción, a través del control de costes de los proyectos. En concreto, se presenta un estudio de caso, la construcción de un centro de educación infantil en la ciudad de Madrid, para cuyo análisis se exponen y analizan los datos necesarios. Los resultados reflejan información interesante, en términos de huellas, sobre los elementos que deben ser controlados y mejorados en el diseño del proyecto, tales como el hormigón y acero.

Palabras clave
Ingeniería de la construcción, impacto ambiental, indicadores ambientales.

ABSTRACT

Within the commitments of the 2030 Agenda, the socio-economic objectives for a sustainable development of society as a whole, stand out, which propose minimizing the impact produced by all the activities of the Public Administration on the environment. Therefore, the creation and retrofitting of its infrastructures, needed for its operation and the services it provides, has a great impact. The goal of this work focuses on a methodological adaptation for the environmental evaluation of the works promoted by public organizations, quantifying and locating the sources of impact with the purpose of taking the measures to minimize them. For this, the footprint family, ecological, carbon, and water, are proposed as indicators, characterized by the simplicity of their message and the ease of their implementation in the construction sector, by controlling project costs. A case study is presented, the construction of an early childhood education center in the city of Madrid, for which the data needed for the calculation are presented and analyzed. The results reflect interesting information in terms of footprints, on the elements that must be controlled and improved in the project design, such as concrete and steel.

Keywords
Construction engineering, Environmental impact, Environmental indicators.

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INTRODUCTION

Within the guidelines outlined by the 2030 Agenda for the Sustainable Development of Spanish society, objectives are established on developing sustainable infrastructures and reducing their impact, as well as guiding business and public activity towards a reduction of greenhouse gas emissions. Among Public Administration activities, the construction of new buildings or retrofitting of existing ones, assume an impact that needs to be quantified to be able to implement measures to minimize this and, at the same time, help in decision making. It has been determined that the construction sector, in its production aspect, accounts for 40% of the consumption of all natural resources, as well as 30% of the energy consumed, while producing more than 30% of the greenhouse gases emitted (Fundación General de la Universidad Complutense de Madrid, 2010). When considering that public works procurement activities in 2019, represented up to 23% of the total amount paid out by the Spanish General State Administration (National Commission of Markets and Competition, 2019), an amount of nearly 1 billion euros, or 5% of the country's GDP, it is possible to provide an idea of the relevant impact of the construction sector on production activities.

The need of defining indicators, whose applications are quick, and whose interpretations are simple, make the Carbon (CF), ecological (EF), and water (WF) footprints, valuable tools to evaluate the impact of the construction process (Zhang, Dzakpasu, Chen & Wang, 2017). They are also successful because the results they produce are understandable for the non-scientific society, and because of their ease of application in decision-making (Bare, Hofstetter, Pennington & Udo de Haes, 2000) and policy. Together, these are called the "footprint family" (Vanham *et al.*, 2019). Footprints are ideal as environmental indicators within public procurement (Kairies, Muñoz & Martínez, 2021) and legislative development on sustainability, despite the need for progress in the standardization of their use (Laurent & Owsianiak, 2017).

First of all, CF as the most widely used, measures the total amount of greenhouse gas (GHG) emissions and is expressed in units of mass of CO_2 equivalent. There are many bibliographic reviews related to using the CF indicator in construction (Geng, Mansouri & Aktas, 2017). However, the results are not always comparable, due to the absence of a methodology that follows international standards (Dossche, Boel & De Corte 2017). For this reason, studies have also been made in recent years to establish scales that allow defining reasonable ranges of CO_2 emissions in construction processes (Chartas, Theodosiou, Kontoleon & Bikas, 2018).

Second, water consumption stands out. Here the WF indicator measures the volume of water used, both directly (water consumed from the network), as well as indirectly, also known as Virtual Water (VW). The concept was formulated by Allan (1993) as an indicator of the freshwater consumed in any production process. Although still in crisis (Velázquez, Madrid & Beltrán, 2011; Beltrán & Velázquez, 2015), the concept has been greatly developed and is useful to achieve better water management associated to buildings. However, few building studies use this indicator. VW in construction is defined as the volume of fresh water consumed to produce building materials from their origin to the factory door. Among the studies, ones from Australia on the tertiary sector that focus on VW consumption during the construction stage compared to the rest of the Building Life Cycle (BLC) stand out (McCormack, Treloar, Palmowski & Crawford, 2007). Crawford and Pullen (2011) also analyzed water in residential BLC over a period of 50 years and concluded that VW in building materials is higher than the direct consumption of homes, showing that water policies should also include virtual consumption. Férriz Papí (2012) made a study on the water consumption used by building materials throughout their life cycle and obtained similar statistical results, during 3 years in 200 projects in Catalonia.

The third indicator in the footprint family is EF, which is conceived as the area of land needed to supply resources (cereals, fodder, firewood, fish and urban land) and to absorb emissions (CO_2) of the society. It measures the productive land area in global hectares (gha). In recent years, some research has confirmed the suitability of the indicator to analyze the environmental impact of buildings. Regarding the building life cycle, the works of González, Marrero and Solís (2015), which develop a quantification methodology for building construction, stand out. Martínez-Rocamora, Solís-Guzmán and Marrero (2016b), for their part, have designed a method to calculate the economic costs and environmental impact during use and maintenance, yielding data in terms of EF. Alba-Rodríguez (2016) proposes the development of a methodology to get to know the environmental viability of the building retrofitting versus their demolition. Freire, Alba and Marrero (2019) determine the EF of elements that are

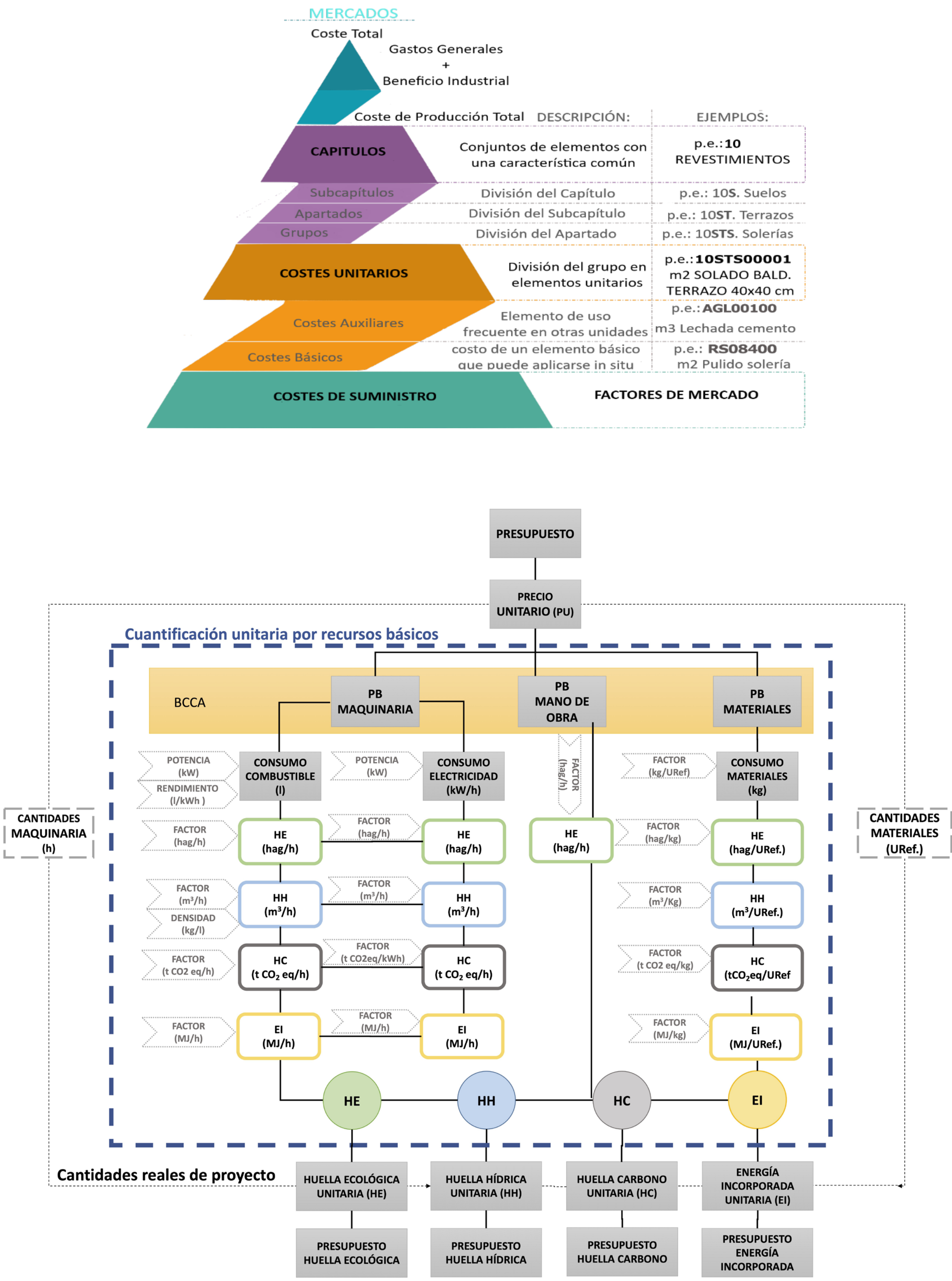


Figure 1. (a) BCCA pricing structure. (b) Application of general methodology to unit costs/prices. Embodied energy (EE) is an intermediate impact which is also calculated. Source: (a) Prepared using Marrero et al., 2020. (b) (Rivero, 2020, p. 39).

part of traditional construction costs and, finally, Rivero (2020) verifies all the stages of the BLC of residential constructions from a new perspective of "environmental budget".

Currently, the Spanish public administration is committed to minimizing the impact of its activities on the environment. This is reinforced by public policies from the European Union for public procurement, which urge that contract awards be made based on a plurality of economic, qualitative and social criteria, giving great relevance to environmental aspects (Public Sector Contracts Law, 2017). As a result, it is necessary to bring project budgets in line with this type of environmental impact assessment methodologies, so that these are adapted to the singularities of public infrastructures. From this perspective, and following the line of the environmental budget, the impact of the construction of a building of the tertiary sector, specifically, a nursery school in Madrid, Spain, is evaluated here. Its global analysis is based on the three footprints presented: carbon, water and ecological.

METHODOLOGY

To achieve the goal set out, the economic works budget is looked at which, considering the cost structure established by the Law on Public Sector Contracts, and its development regulation (Regulation of the Law on Public Sector Contracts, 2001), this is broken down into Basic (BP), Auxiliary (AP) and Unit (UP) Prices, which are assigned to the direct and indirect costs of each unit of work. Figure 1a shows the pyramidal classification of this cost/price structure in the particular case of its application in the Andalusian Construction Cost Bank (Marrero & Ramírez de Arellano, 2010). Subsequently, with the measurement of work unit prices or UP, the amount of each one is obtained and, together, the total budget of the work.

The determination of the different indicators, EF, CF and WF (Figure 1-b) is done following the methodology defined by Freire and Marrero (2015a). The impact of materials and machinery is calculated by converting the unit of measurement of the budget to kg. The impacts per kg are obtained from the life cycle analysis database, Ecoinvent LCA (Ecoinvent Center, 2013), which is known as being one of the most complete databases at a European level (Martínez-Rocamora *et al*., 2016a), and its integration is done using Simapro LCA software (PRé Sustainability, 2016). The work is similar to that carried out for the CF calculation with the SOFIAS tool, which uses data from the environmental declarations of products, OpenDAP, or the BEDEC platform, developed by the Catalonia Institute of Construction Technology [ITeC, in Spanish] (ITeC, 2013). Figure 1-b schematically shows the integration of footprints into construction budgets for the particular case of the Andalusian Bank of Construction Costs (BCCA) (Marrero & Ramírez de Arellano, 2010). The formulation is summarized in Table 1 for EF, and Table 3 for CF and WF. The methodology, which is organized into three levels (input data, impacts and footprints), allows obtaining, from the general works data and the economic data of the budget, the environmental impact of the project. This study evaluates, within the life cycle, the construction stage that includes what is consumed in the works, so that the contours of the impacts correspond to the measurement criteria in the budget.

On-site machinery is calculated based on engine power and hours of use on-site, while the energy consumed in kWh that will be converted into CO_2 emissions is determined (Freire & Marrero, 2015a). Construction and Demolition Waste (C&D) of the transport machinery is also included in the calculation. This part of the construction budget is included, in an independent chapter, as established by RD 105/2008 (Marrero & Ramírez de Arellano, 2010) which regulates C&D management in Spain.

In the particular case of the impact of labor, which is only calculated in the EF indicator, the food consumed as the worker's source of energy is determined (Table 2). A typical menu for an adult consisting of meat, fish, cereals and water is used as its basis (Grunewald, Galli, Katsunori, Halle & Gressot, 2015), and the relative EF is determined in: pastures, sea and crops. The EF of the workforce also includes their Municipal Solid Waste (MSW), which corresponds to the average generated by each worker, and its corresponding emission factors.

EF also takes into account the impact related to the area of land occupied, which will not be agriculturally productive, and the water consumed in the execution. All impacts are assigned a partial EF in different categories of the indicator (sea, pastures, crops, soil) to, ultimately, through conversion factors, obtain the global footprint in an equivalent area.

In the direct consumption of water and energy in the works themselves, the value of consumption in cubic meters of water has been empirically established according to the built area (González *et al*., 2015), where the transformation into CO_2 emissions applies, through the energy in kWh needed to obtain one cubic meter of water. Similarly, the electricity consumed is determined (Freire and Marrero, 2015b).

ECOLOGICAL FOOTPRINT	equation n°
Workforce	
EF_{FOOD}: EF produced by food consumption (gha)	
$EF_{FOOD\,i} = (H_{WORK} / H_D) \times (PC/100) \times (EF_i/365)$	1
H_{WORK}: Number of hours worked (h)	
H_D : Number of hours worked per day (8h/day/person)	
PC: Percentage that represents the breakfast and lunch of worker's food (60%)	
EF_i: Food consumption footprint in EF category i (gha/person) (Table 2)	
365: days in a year	
EF_{MSW}: EF produced by municipal solid waste (gha)	
$EF_{MSW} = (H_{WORK} \times R_{MSW} \times E_{MSW} \times 0.72)/A_F) \times EF_F$	2
R_{MSW}: Quantity of MSW produced per working hour (0.000077 t/h per person) (EUROSTAT 2015);	
E_{MSW}: emission factor by waste (0.244 t CO_2/ tMSW) (Almasi & Milios, 2013)	
0.72: CO_2 absorbed by forests. Remaining 28% = ocean absorption(Borucke et al., 2013)	
A_F: forest absorption factor (3.59 t CO_2/ha)	
EF_F: forest equivalence factor (gha/ha)	
Materials	
EF_{MAT}: EF of Building materials (ha)	
$EF_{MAT} = ((\Sigma_i\ Cm_i \times E_{MAT}) \times 0.72)/A_F) \times EF_F + EF_{TRAN} \times Cm$	3
Cm_i: Consumption of material i (kg)	
$E_{MAT:}$ emissions by material (kg CO_2/kg material)	
EF_{TRAN}: ecological footprint of transport of building materials (ha/kg)	
Machinery	
V: fuel consumption (liters) (50)	
V = (Pow x TU x Perf)	4
Pow: electric machinery motor power (kW)	
TU: time used according to measurements (hours)	
Perf: fuel consumed by the engine whether diesel or gasoline (l / kWh)	
EF_{COMB}: EF of (fossil) fuel consumption of machinery (gha)	
$EF_{COMB} = ((V \times E_{COMB} \times 0.72)/A_F) \times EF_F$	5
E_{COMB} fuel emission factor (kg CO_2/liter). Spanish data: 2.616 kg CO_2/ l (IDAE, 2011);	
EF_{ELEC}: EF of machinery electricity consumption (gha)	
$EF_{ELEC} = ((Pow \times TU) \times E_{ELEC} \times 0.72)/A_F) \times EF_F$	6
E_{ELECT} energy mix emission factor (kg CO_2/kWh). Spanish data: 0.248 kg CO_2/ kWh (REE, 2014).	
Water consumed	
EF_{WATER}: EF of water consumed (gha)	
$EF_{WATER} = ((C \times EI_{WATER} \times E_{WATER} \times 0.72)/A_F) \times EF_F$	7
C: consumption (m^3)	
EI_{WATER}: water energy intensity (0.44 kWh/m^3) (EMASESA, 2005)	
E_{WATER}: electricity emission factor (0.000248 kg CO_2/kWh) (REE, 2014)	
Area consumed	
EF_{sur}: EF of area consumed (gha)	
$_{EFsur} = S \times FE_x$	8
S: direct occupation area (ha)	
FEX: built area equivalence factor (gha/ha).	

Table 1. Formulation of the EF model. Source: Preparation by the Authors.

Crops (10^{-3} gha)		Pastures (10^{-3} gha)	Sea (10^{-3} gha)	Fossil (10^{-3} gha)
1,45	0,27	0,41	0,49	

Table 2. EF of the daily food consumption per year and person in Spain. Source: González Vallejo (2017, p. 270).

CARBON FOOTPRINT	
Materials	
CF_{MAT}: CF of Building materials (tCO_2eq)	
$CF_{MAT} = (\sum_i Cm_i \times X_{MAT}) + (CF_{TRAN} \times Cm_i)$	9
Cm_i: consumption of material i (kg)	
E_{MAT} emissions by material (tCO_2eq/kg of material)	
HC_{TRAN}: carbon footprint of the transport of building materials (tCO_2eq / kg)	
Machinery	
V: fuel consumption (liters)	
V = (Pow x TU x Perf)	10
Pow: electric machinery motor power (kW)	
TU: time used according to measurements (hours)	
Perf: fuel consumed by the engine whether diesel or gasoline (l/kWh)	
CF_{COMB}: CF (fossil) fuel consumption of machinery (tCO_2eq)	
$CF_{COMB} = V \times E_{COMB}$	11
E_{COMB} fuel emission factor (tCO_2eq/liters). Data: 2.616 kg CO_2/ l (IDAE, 2011);	
CF_{ELEC}: CF of machinery electricity consumption (tCO_2eq)	
$CF_{ELEC} = (Pow \times TU) \times E_{ELEC}$	12
E_{ELEC} energy mix emission factor (kg CO_2/kWh). Data: 0.248 kg CO_2/ kWh (REE, 2014).	
WATER FOOTPRINT	
Building materials	
WFma: Partial water footprint of material consumption (m^3)	
$$\boldsymbol{WF_{ma} = \sum (C_{ma_i} \cdot VW_{ma_i})}$$	13
C_{mai}: Material consumption i (kg)	
VW_{mai}: Virtual water of material i (m^3/kg)	
WF_{tr}: Partial footprint of material transportation (m^3)	
$$\boldsymbol{WF_{tr} = \sum (\frac{W_{ma_i}}{T_{cap}} \cdot D_{ma}) \cdot T_{con} \cdot VW_f}$$	14
W_{mai}: Weight of consumption of material i (t)	
T_{cap}: Transport capacity (t)	
D_{ma}: Average transport distance (km)	
T_{con}: Transport fuel consumption (l/100 km)	
VW_f: Virtual water factor of the fuel (m^3/liter)	
Machinery	
WF_{mc}: Partial water footprint of machinery (m^3)	
$$\boldsymbol{WF_{mc} = \sum (H_{mc_i} \cdot C_{f_i} \cdot VW_{f_i})}$$	15
H_{mci}: Hours of use of machinery i (h)	
C_{fi}: Consumption factor of machinery i (l/h or kW)	
E_{fi}: Virtual water factor of fuel used by machinery i (m^3/l or m^3/kWh)	

Table 3. Formulation of CF and WF models. Source: Preparation by the Authors.

Figure 2. a) Main elevation and sides of the nursery school in El Goloso. (b) Real photo. Source: a) Taken from Barbero (2018, p. 352). (b) Made using Google maps.

CASE STUDY

Spain has 34,168 non-university educational centers, according to the State Register of Non-University Teaching Centers of the Ministry of Education, Culture and Sport. Of these, most are public (65.9%). Therefore, as a representative public building, for the case study, the impact of the construction of a nursery school in El Goloso, Madrid is calculated. The building has two floors, a total built area of 874.72m^2, and is fully equipped to accommodate 84 children. A building has been chosen with the most frequent constructive solutions of current public buildings in Spain, and considers a wide variety of different work items to house different staff and student numbers along with facilities. It consists of classrooms, toilets, kitchen, nurse's station, and administration. Its floor plan is built in a U, around the partially covered playground, and its access is through the main facade (Figure 2). Its budget is €1,834,831.14 and it has been built over a 12-month period.

Constructively, it is supported on reinforced concrete slab foundations, with a suspended floor structure on the ground floor, and a reinforced concrete upper slab, the latter supported on reinforced concrete pillars. The main enclosure is characterized by its ventilated facade finished in lacquered aluminum panels and rock wool insulation, while the side and rear facades have a double brickwork enclosure, coated with a white finish one coat mortar. The interior partitions are made using a laminated drywall system and removable false ceilings. The building's roof is flat and landscaped, and the playground has a green wall and rubber flooring adapted for children. The interior carpentry is made of wood and the exterior of aluminum, with thermal bridges and double glazing. The interior finishes are linoleum floors, except in the kitchen and toilets, which are non-slip stoneware. Regarding the fittings, the building has the basic sanitation, water, electricity, air conditioning, communications and fire protection elements. As for the urbanization, the paving and walkways connecting the general facilities and surrounding roads are partly replaced.

RESULTS AND DISCUSSION

The first step consists in obtaining, from life cycle analysis databases, the impact by building material families (Table 4). These data apply to the quantities of project units included in the budget.

The project obtained a total EF of 361.6 global hectares/year (Table 5), where activities related to masonry work correspond to 17.3% of the total, the highest EF, followed by the foundation and the structure, with 14.4% and 14.0%, respectively. The total weight of the building materials is 1,986,086.61 kg, which represents

MATERIAL	WF (m^3/t)	EF (hag/t)	CF (t CO_2 eq. /t)
Soil	0	0,005	0,004
Wood	2,62	-0,483	-0,990
Concrete	1,68	0,057	0,112
Asphalt	3,0	0,098	0,21
Ceramics	1,0	0,107	0,22
Aggregates and stones	1,2	0,005	0,004
Metals	81	0,907	2,01
Plastics	456	0,898	1,97
Glass	17	0,30	0,669
Mortar and plaster	67	0,294	0,610

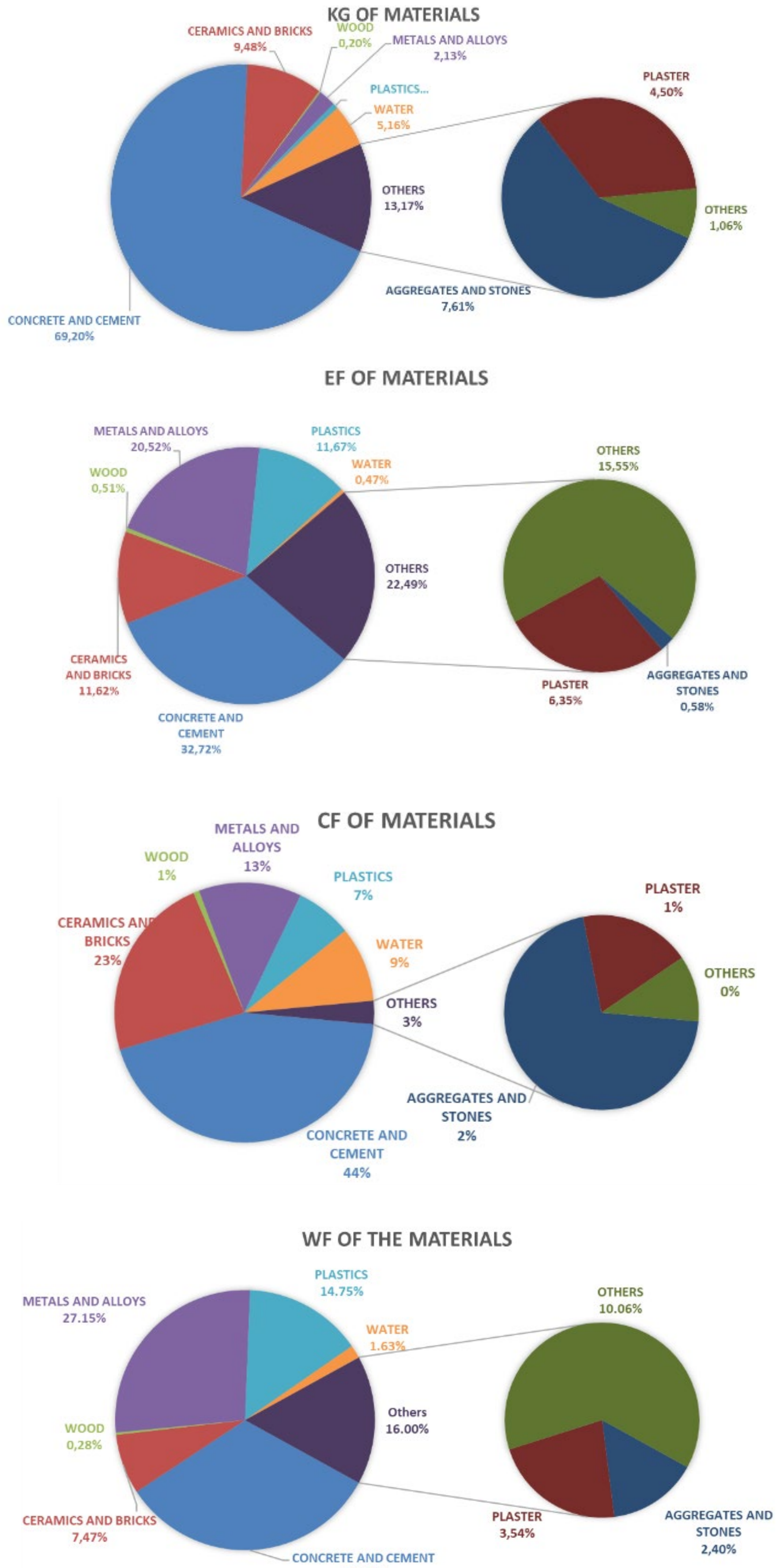
Table 4. Footprints of material families per ton. Source: Preparation by the Authors.

Project sections	EF (gha)	CF (tCO2eq)	WF (m3)
C01.: Demolitions	22,747	53,426	685,630
C02.: Land preparation	23,270	57,177	705,403
C03.: Foundation	52,062	122,665	2,012,721
C04.: Sanitation	7,056	17.153	301,713
C05.: Structure	50,776	116,693	1,904,439
C06.: Masonry	62,697	138,381	2,107,457
C07.: Roof	13,188	26.854	723,513
C08. 1: Air-conditioning and ventilation	5,812	11.913	387,321
C08. 2: Electrical fittings	4,988	15.967	176,894
C08. 3: Water fittings (supply and sewer)	13,206	26.404	190,653
C08. 4: Hot water production fittings	9,524	23.723	759,060
C08. 5: Accessibility fittings	14,628	32.875	297,379
C09. Insulation	3,133	8.874	148,149
C10. Coating	30,980	66,404	1,783,008
C11. Carpentry, security and protection	7,866	16,487	380,069
C12. Glazing	3,719	8,292	250,583
C13. Paint	6,671	10,516	268,751
C15. Urbanization	29,263	64,923	949,244
TOTAL	361,586	818,728	14,031,988

Table 5. Results obtained by project sections.Source: Authors ' elaboration.

an impact of 2,270.54 kg/m^2. While the built area generates 95,136.07 kg of C&D or 108.76 kg/m^2.

The materials with the greatest environmental impact, with more than 69% of the EF, are presented in this order: concrete, metals and alloys, and ceramics (Figure 3). Given this, changes in the embodied energy in manufacturing processes, or in emissions from their processes, such as using recycled materials or ones with a high waste content, can significantly reduce the project's footprint (Freire *et al.*, 2019). These materials are also the ones that weigh the most: concrete is almost 70% of the total weight, and the weight of water which represents



(a)

(b)

(c)

(d)

Figure 3. (a) The weight of materials in the project. Footprints of materials: (b) ecological; (c) carbon; (d) water. Source: Preparation by the Authors.

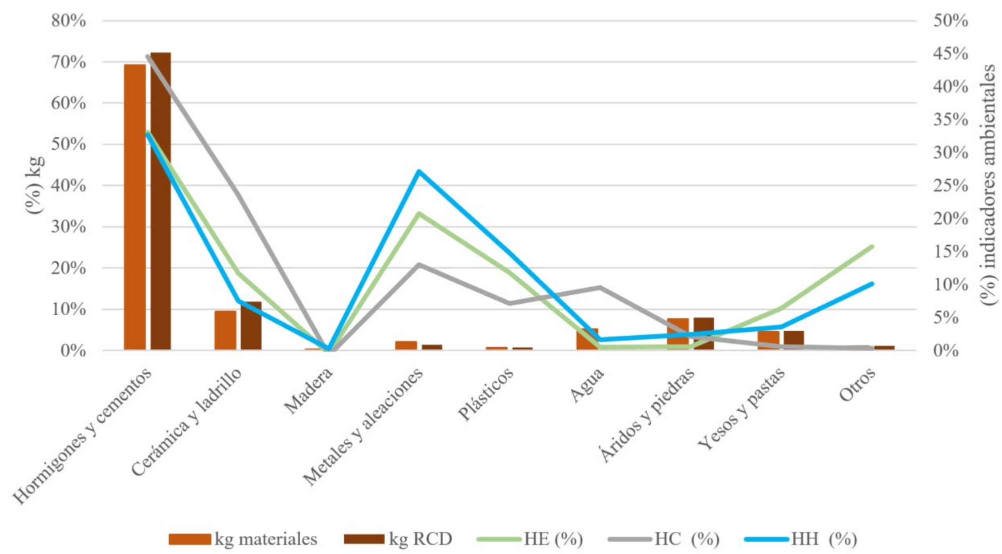


Figure 4. Impacts by material families. Source: Preparation by the Authors.

15% of the total, also stands out. In the calculation of the other footprints, as in the work of Marrero, Rivero and Alba (2020), it is the same materials that register the greatest impact. Construction materials account for 80% of the total project, compared to 18.5% of machinery; while the impact of workers only accounts for 1.5% of the total.

Regarding CF (Figure 3), the high impact of concrete in the process is confirmed with 44%, followed by ceramic elements with 23%, while metallic materials and alloys account for 13% of its CF. Wood is at the opposite end of the scale, with only 1% of the impact. This footprint has the same proportions as the ecological one, due to the great importance of building materials in both calculations. A total CF impact of 653.62 tCO2eq and an impact of 0.7472 tCO2eq/m^2 is calculated.

The WF of the materials is in line with the previous two, as shown in Figure 4, although the impact of the concrete compared to the CF is reduced, dropping to 32%. Meanwhile, the impact of metals and alloys is increased, and the importance of ceramic materials falls to 7%. The low impact maintained by wood stands out. The total volume of WF is estimated at 12,601 m^3, which means an impact of 14,340 m^3/m^2 from the construction. Figure 4 shows the results of the impact of construction materials in percentages, which allows comparing the importance of each type and, simultaneously, presenting the respective waste generated. It can be seen how the water footprint is less important in ceramic materials than in the case of metals, unlike with the carbon footprint, so a single indicator does not seem enough to highlight the materials that must be improved in the project. Concrete and cement are the most widely used materials, with the highest amount of C&D and, at the same time, the most impactful in all categories, so taking actions to reduce their impact will represent an overall improvement of the project. On the other hand, metals, although not important in weight and waste, their impact is very high in all footprints and should be the second category to be improved when retrofitting with more sustainable constructive solutions.

In the analysis by project sections, the results are very similar to those obtained by other authors (González, Muñoz Sanguinetti & Marrero, 2019). In the case of social housing analysis, where the sections with the greatest impact are foundations, structures and masonry, once again, due to the materials being used in large volumes, these involve a lot of energy and CO_2 emissions in their manufacturing processes. It can therefore be determined that, despite the constructive and technical differences of public educational buildings, which are equipped with larger electromechanical fittings and more unique materials, their environmental impact is in line with residential buildings.

CONCLUSIONS

The model proposed by Rivero (2020) combines footprint evaluation with the economic valuation of building construction. With this work, the adaptability of existing consolidated methodology for the environmental evaluation and control of projects of any type of buildings is verified, since this is based on a cost structure or systematic price classification systems.

On being a methodology that is supported by the current classification systems, it allows sector professionals to quickly prepare an economic budget that can include the environmental impact. The footprint analysis includes building materials from their origin to the worksite, for all the elements that are part of the project. It also includes labor, using its source of energy (food intake), and machinery, with its energy consumption.

This methodology can be easily and satisfactorily implemented by the Spanish public administration. This is thanks to the fact that it comes from the traditional works classification model, which is widely used by the technical experts involved in the construction process. This study used the systematic classification of the Andalusian Construction Cost Bank, but it could be replicated with other domestic classifications or costs banks. The clarity of the data obtained and its easy interpretation by non-specialized personnel make the model a valuable tool to assess the environmental impact of construction.

The main difference between public and private projects lies in the constructive solutions used, as well as in the consumption of resources by built area. It would be advisable to apply the model to other types of public constructions such as museums, offices, communication centers, etc., both in those that are built in new floor plans, and in those that retrofit existing buildings, within the spectrum of public infrastructures, given the constructive singularities of each of them. In this way, it is possible to define reference impacts that serve as a basis for making environmental decisions in the construction process. The results obtained in this work serve as a starting point to generate new impact examples of public buildings and databases for future research, to compare and make improvement proposals in the designs of the projects evaluated.

As a conclusion, and as the footprint calculation is based on the works budget, bidder proposal evaluation systems can be developed within public procurement procedures to minimize the impact of construction that also form part of the contract specifications. This could provide technical support to assess environmental improvement measures in the public tender.

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